Analyzing the Universe

Content:

Images, The Nature Of Light And An Introduction To DS9

1 The Nature Of Images

Welcome to 'Analyzing the Universe.' To start with, I want to talk to you about images.

Why? What is the big deal? We know all about them, right?

After all, our lives are inundated with images, images to cajole us into buying something, images to remind us of an event or a person, images to please our artistic tastes.

However, we take them for granted. Even our phones can now function as cameras. It is hard to imagine that a time even existed when we were not besieged with photographs. Yet it is only around 1840 when people were astonished to find that they could now capture a moment in time in the minutest detail, far surpassing any method that had ever come before. A revolution ensued that is still in progress today. The mirror with a memory is what the early daguerreotypes were called. In addition, since photographic images of one form or another constitute almost the sole means of analyzing astronomical objects, it behooves us to understand exactly what is involved in obtaining these images, how we perceive them, and what they can tell us. This is what we will be exploring in our first few lectures.

1.1 Analyzing Astronomical Objects

Illustration 1 : Image of the Moon (1851)

The earliest photographs of an astronomical object were naturally of the moon. This image dates from 1851 taken by John Adams Whipple. Although Daguerre apparently took one in 1839, his laboratory and its contents sadly burned to the ground soon thereafter. What a loss! However, some of the early photos of the 19th century were distinctly eerie. Just look at this street scene taken by Daguerre in 1838 of the Boulevard du Temple.

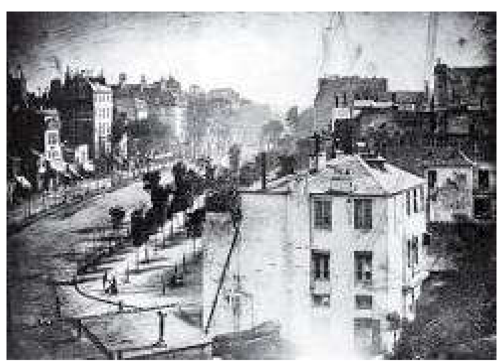


Illustration 2 : Boulevard du Temple (Paris, 1838)

A street always teeming with people, and horse drawn carriages in Paris, yet no one is to be seen, except for a tiny figure at the left, who is getting his shoes shined, and thus was motionless for long enough, to have his image appear on the photographic plate. Not every other moving object could register on it. Thus began a quest, still with us today for speed, speed, and more speed, therefore, that we can capture progressively shorter and shorter time intervals. We want our cameras, our telescopes, and even our iPhones to be more and more sensitive to light. When they do become more sensitive, we can acquire an image in less time, and we say that we have increased the temporal resolution of our observation. Today, we can capture in $^{1}/_{10,000}$ of a second what took Daguerre hours to register on his camera.

What is more, we can record not only the day that an observation or photograph is taken, but using sophisticated electronics, we can time-tag each individual packet of light as it is received into our instruments. We call these packets of light photons, and these photons are almost the exclusive providers of all of our astronomical data. Therefore, the first characteristic of our image description is our ability to record the time of arrival of light. This allows us to see whether the object we are looking at is changing its intensity or light output as a function of time. In other words, we can search for time variability of cosmic sources.

In addition to the time stamp and exposure sensitivity of film or digital detectors, each individual light gathering instrument, whether it is your eyes, a camera lens or a huge satellite driven telescope, has an inherent spatial resolution as well, which is characterized by its ability to distinguish nearby regions from each other. Just imagine you are looking at an automobile approaching at night. From far away, first the headlights appear together on top on one another. You cannot really tell that there are two of them. However, if you look through a pair of binoculars, you can easily distinguish them. We can see how this ability to see parts of an object can change quite dramatically by comparing two observations of CAS-A, an X-ray emitting supernova remnant, whose light first reached the earth about 300 years ago.

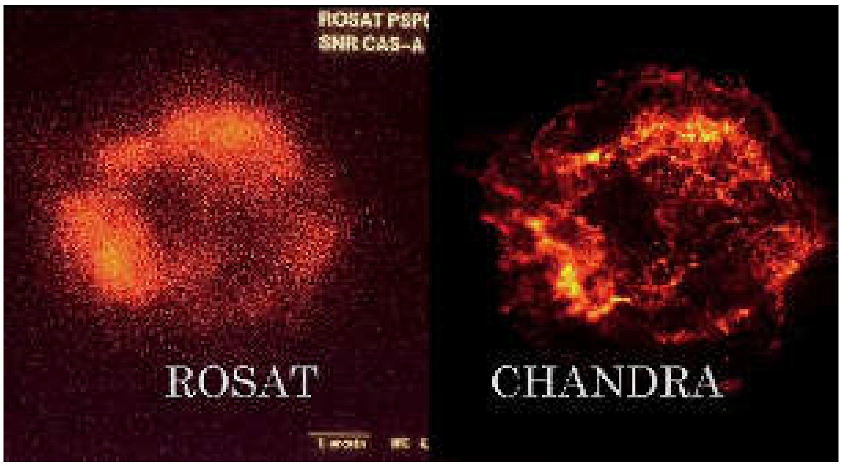


Illustration 3 : X-Ray images of CAS-A (Supernova remnant)

We will have more to say about this object in coming weeks. However, for now I just want you to examine two images of this object, one taken about 20 years ago with a Roentgen satellite, or ROSAT for short, and the other from NASA's CHANDRA satellite less than 5 years later. The difference is positively breathtaking. Things change quickly in the world of X-ray astrophysics. These two images barely look like the same object, but we know they are the same since we are pointing our satellites at the same point in space.

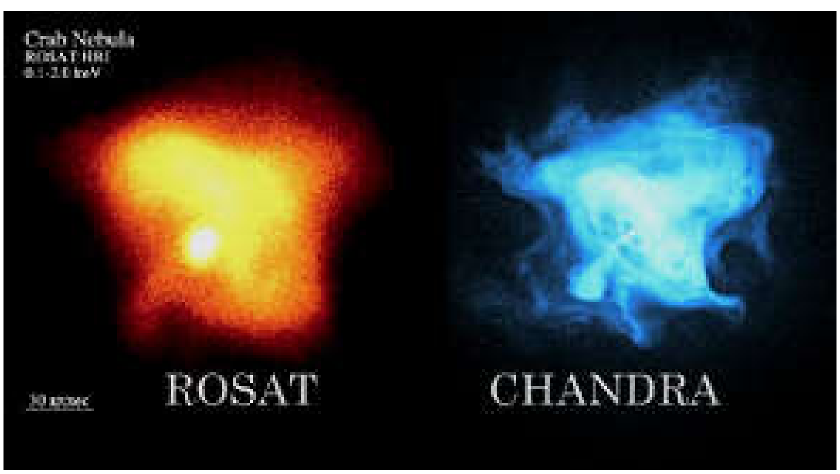


Illustration 4 : X-Ray images of the Crab Nebula

Here is another pair of images of the Crab Nebulae from the same two satellites. You can see that with better spatial resolution, we have an increased ability to examine individual parts of an object and compare those regions with one another. This spatial resolution is a function of several aspects of our instrument among which is its diameter: the bigger, the better. Indeed, improved resolution is a primary reason why we make bigger and bigger telescopes. It is not, as is usually thought, because we want to magnify things more. Therefore, now we have our second bit of imaging information, namely, the spatial position that each photon came from.

Illustration 5 : Comparison between colored and b/w images

What else can images tell us?

Let us look at these two photographs of the Flatiron building, the first skyscraper ever built in New York City in 1902.

What is the obvious difference between these two images?

Right, one is in color, the other in black and white. In one, we have energy information. For example, blue light is more energetic than red light. X-rays are more energetic than blue light.

You might say then, why bother with the black and white image at all?

Aside from artistic considerations though, black and white representations of objects can be more useful than color ones at times. Consider, for example, the red facade on the left hand side of the image across the street from the Flatiron building.

Is it brighter than the adjacent sky area?

Since our eyes respond differently to blue and red light, the answer is not obvious. However, we can get the answer with the black and white rendition. There you can clearly see that it is darker than the surrounding sky. This will be important when we consider X-ray images in detail. After all, our eyes cannot see X-rays at all. We are not super men or women. Therefore, any representation of an X-ray source is going to be a bit problematical, and we will discuss this at length shortly. Therefore, the third clue that our astronomical images can provide is the energy of each photon as well as how many photons of each energy are emitted each second. We will see that this so-called energy spectrum becomes a vital fingerprint for understanding the chemical composition of astronomical objects as well as giving us insight into the energy production mechanisms governing their radiation. Just as fluorescent lamps work differently from ordinary so-called Tungsten light bulbs, so do cosmic sources have different ways to produce their energy. Therefore, the energy spectrum can tell us what the object is made of, and how it produces its light, and that is it.

All we can glean from the tiny pinpoints of light coming from distant objects scattered about the universe are these three bits of data encoded into each photon. In addition, from these data we can construct models to understand the incredibly diverse inhabitants of the cosmos. The fact that we can do this at all is simply astonishing, and it certainly becomes an exciting and interesting process to undertake. Therefore, let us move on, and get a good look at an image, up close and personal.

Illustration 6 : Wisner technical field camera I

What you see mounted on this tripod is a true work of art. It is a hand-crafted camera, made entirely by hand by Ron Wisner in Massachusetts, called a Wisner technical field camera. This is one of the earliest cameras he ever made. If we zoom in, you might be able to see the serial number in the lower right hand corner (Number 257). What you see here on top is the ground glass. That is where the image will be formed that you can see with your eyes. If you are using it as you would a regular camera, you put in a piece of sheet film, and take your photograph that way, but you'll see lots of knobs and all sorts of adjusting things that can be utilized to do various perspective control items.

Illustration 7 : Wisner technical field camera II

Okay, here is the camera, set up. All of these controls here allow you to raise and lower or shift one way or another, the lens relative to the film. You know how you always take a photograph of a building, and in order to get the whole building in the field of view you tip your camera back, and that makes the building lean over, looks like it is falling over. Well, with this camera, all you have to do is raise up the front of the lens, and that will never happen. Perspective control is a vital reason why view cameras have remained popular up to the present day.

Illustration 8 : Wisner technical field camera III

Okay, this is the place where you can actually view your image. What normally you would do when you use this camera is you would close your shutter, and then you simply put the sheet film holder in. Now you can set up your camera after you have focused to give you the right exposure and pull your dark slide. Take your photograph; put the dark slide back in, take out your film holder. We are not going to do that, but that is the procedure. What we are going to do though is try to see what the image looks like.

Illustration 9 : Image as you sees it through a 'Wisner'

What do you see in the image that is presented on your computer screen that is so unusual?

This is actually the way that all images are formed, even the image of anything that you look with your eyes.

Therefore, what is going on here?

2 Image Formation

What do you see in the image that was presented in the last section that is so unusual? This is, so we have just seen that the image that we produce inside of our view camera is upside down. Now, how can this happen? Why does it happen? Well, in order to understand that, we are going to look at the way images form in kind of an odd situation. However, before we do that, I just want to show you what would happen, if we did not have a lens at our disposal.

Illustration 10 : Image taken by a 'normal' camera

Here is a camera. Here is something we can take a photo. Click. There it is.

Can you actually see that?

I hope that in focus, does not matter whether it is in focus. You can see there is stuff there.

Illustration 11 : Image taken without a lens

Now, let us do the same thing without the lens. We will take the lens off, and here it is! Here is our non-image. All you see is, more or less, uniform, nothing.

How does that happen? Why does that happen?

Well, light spreads out from a point in all directions. We rather assume that, but in fact, there is real proof of that every single time you go outside, and you point out an object to a friend that is walking by you. You say oh, look at that big airplane in the sky, and your friend says yes.

How come both of you can see the same object?

It is because light that enters your eyes is a different set of photons then the light that is entering your friend's eyes. Therefore, let us imagine we have kind of this silly situation. For some reason, whenever we have images formed in any physics textbook, they always use an arrow. Therefore, let us stay with that, because it is actually very convenient, and it is good for me, because I cannot draw anything. We will imagine that we do not have any lens at all, and we have just some sort of piece of film or some sort of digital detector nearby this arrow. We are going to take a picture of this arrow using our digital detector.

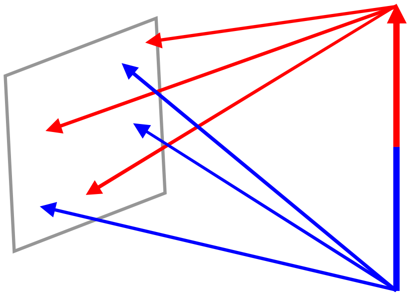


Illustration 12 : Pathways of light from an image to a detector

What you just saw with my digital camera really points out to you that you cannot have an image without some sort of way to focus light. Okay? We take this for granted. However, let us look at this. Here is our picture of an arrow, and here is our film.

Why we do not get an image of that arrow when we just have a piece of film just raw exposed to this particular object?

Well the reason is very clear. The light from the tip of the arrow goes here, some of the light from the tip of the arrow goes here, and some of the light from the tip of the arrow goes there. In fact, light from the arrow tip will spread out completely over the entire piece of film. On the other hand, the tail of the arrow, some of that light will go here, some of that light will go here, some of that light will go here, and you can see pretty clearly that you are just going to have a complete mess. There is going to be light coming from all parts of the arrow on all parts of your detector. Therefore, you are not going to get an image.

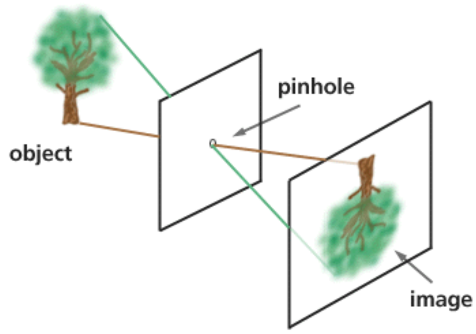


Illustration 13 : Pathways of light from an image to a detector through a pinhole

Now let us imagine something a little bit different. In order to make sure that the light from only one part of the arrow goes to only one part of the lens, let us imagine that we set up the following. We have a sheet of film, and in between the sheet of film, or our digital detector, we are going to place just a little pinhole. Therefore, we have a tiny hole in the middle between the arrow and our detector. Now, look and see what happens to the arrow tip. Light can come through the hole in the pinhole. You see that all the other rays of light coming from the tip of the arrow are blocked. Therefore, the only place that the tip of the arrow will show on our detector is down there. We will see, eventually, if we were to turn that film in the direction, so we can see it, an image of the tip of the arrow. Also, light from the tail of the arrow that will go through our pinhole sit over here! Moreover, all the other rays of light that might have affected our detector in an adverse manner as far as not allowing any image to form will be blocked by our pinhole. Now we will see that we will end up with the tail of the arrow. Of course, all the intermediate parts of the object will also travel through the pinhole and form their appropriate place on our detector. Low and behold, we have an upside-down image.

Now, one of the big disadvantages of a pinhole is that it is a pinhole. There is just a little tiny amount of light going through that.

Would it not be great if instead of wasting all of the light that is blocked by the pinhole we could actually use that light, and form an image with many, many more photons, and, therefore, in a much shorter period of time?

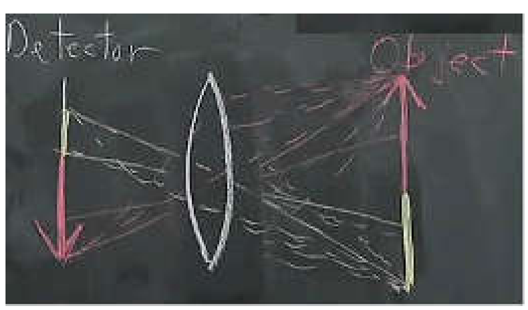


Illustration 14 : Pathways of light from an image to a detector through a lens

Well, that is exactly what a lens does. It is really, in a certain sense, a collection of little pinholes. The pinholes of which are arranged so that all of the light comes to focus on a single point. That is the key for formation of an image. Therefore, you can see it is inevitable that we end up with an image that is upside-down if it is a real image, if it is something that has energy associated with it.

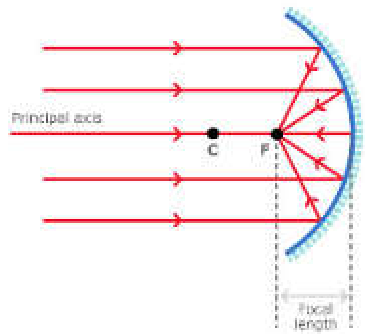


Illustration 15 : Reflection of light on a concave mirror

There is another way to form an image, and that is using a curved mirror. Rather than using my terrible artwork to do this, we will actually return to our computer station, and see how mirror images work when we use a curved surface. Keep in mind when we do this, that there are going to be differences between these mirrors, which are mirrors that are curved, and the images that you get when you stand in front of your mirror in your room and look at yourself. You are obviously right side up in that mirror, or at least in the same upside sense that the brain kind of flips around, and all of that stuff.

Why does the brain not flip the view of the camera image upside-down?

If it is upside-down, and it is supposed to flip everything that is upside down right side up, you have your camera image upside-down.

Why is it not right side up?

Good question. One other thing I might add is that there are limitations that we have currently with lenses. Let us draw a lens so we can actually see what some of those limitations are. Instead of our pinhole, we have a lens that is now going to serve the same purpose as our pinhole, but allow all of the light, or at least more of the light, to kind of come through, and be focused at the proper place.

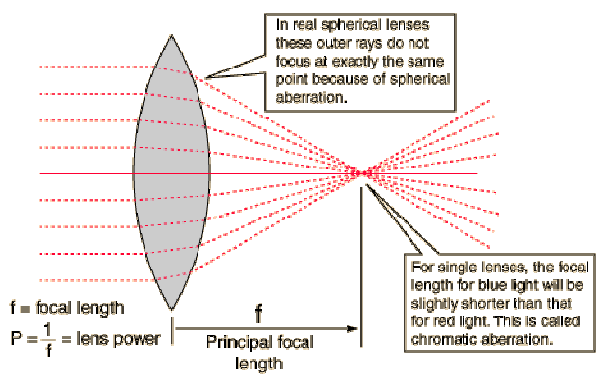


Illustration 16 : Limitations of small lenses

Whoops, not very well. The point is, and this is the thing to take away from this, is that the lens is very thin at the edges. It is very, very hard to make a large piece of glass that is thin around its circumference. In fact, this is the primary reason, or one of the primary reasons, why refracting telescopes that use lenses instead of mirrors are limited. Currently, the largest refracting telescope in existence is just about 40” in diameter, and a new one that size has not been built in many, many years.

You might say; why do we need the lens shape like this?

Well, in fact it is the lens being shaped like this that allows all of the light to know where to go. This has to do with a principle called the principle of least time that Pierre Fermat thought about a very long time ago, and its part of the way that our modern lenses for cameras are designed today. However, very recently, people have started thinking about the possibility of making a flat lens. The way you do that is a very strange idea that has to do with the way light bends as it goes through an object. Therefore, you can see, or you ought to be able to see, that the larger the diameters of the lens, the more light you can gather, and that really is the reason for having large telescopes. If we can somehow get images formed in a way that allows us to gather even more light than is currently possible from a particular object in space, we will be able to do astronomy even more efficiently than we can do it today.

3 Skipping Stones And X-Ray Images

At this point, please watch "Analyzing the Universe001.mp4"

Video 1 : Skipping stones

Therefore, what is all this has to do with X-ray astronomy?

It turns out that unlike visible light, which you can image, using a set of mirrors or lenses in a very straightforward fashion. X-rays do not quite work that way.

We have already talked about imaging with a lens. It turns out that when you use mirrors, the process is similar. The reason that mirrors are used though is that it is much easier to support a large mirror, because you have that entire area behind it to make sure that things do not warp or change their dimensions. When you look at a lens, it is supported just around its periphery, and when you do that, you run the risk of having the lens actually sag. Therefore, the largest telescopes for many years have always been made with mirrors.

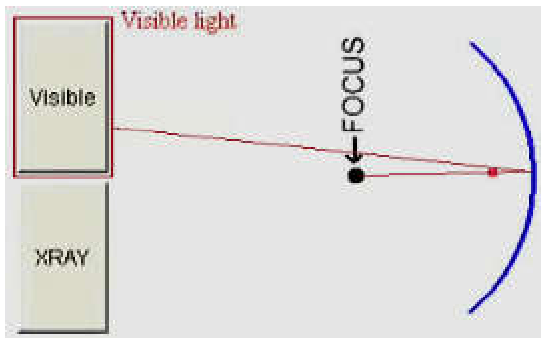


Illustration 17 : Mirror pathway of a visible photon

Let us see what happens when we look at visible versus X-ray light. Here you see what happens to visible light. Light comes from the stars, hits the mirror, and no matter where it hits the mirror, it comes to a focus, and you can collect the photons and look at your image.

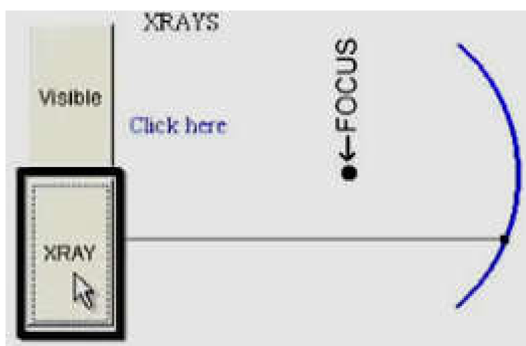


Illustration 18 : X-rays showing no reflection

Unfortunately, what happens in X-rays is that, look. They just do not go anywhere. They get absorbed and because they get absorbed, we would lose all of that precious information coming from the Stars.

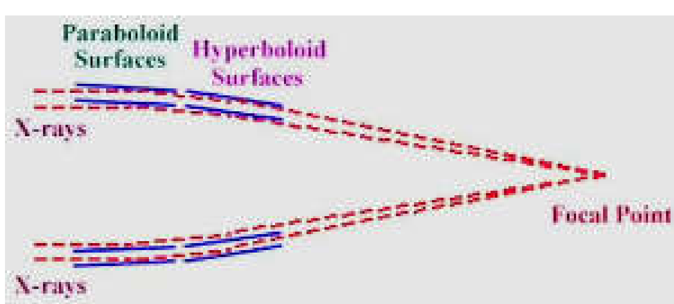


Illustration 19 : Pathways in an X-ray telescope

However, fortunately, like skipping stones along our pond, if we allow the X-rays to come incident to a set of mirrors at a grazing angle it turns out that we can reflect them, and thereby make an X-ray image. Let us see what that looks like.

If you actually have X-rays incident on a set of nerves at grazing incidents very similar to the way we just skipped some stones on the pond, it turns out that you can image them in a way that allows you to use a set of nested mirrors similar to the way we use regular mirrors for regular telescopes. This is what it looks like. The X-rays come in; hit first the set of parabolic mirrors and then at grazing incidence, hit hyperbolic mirrors. Then on they go towards the focal point, where our X-ray detector is located.

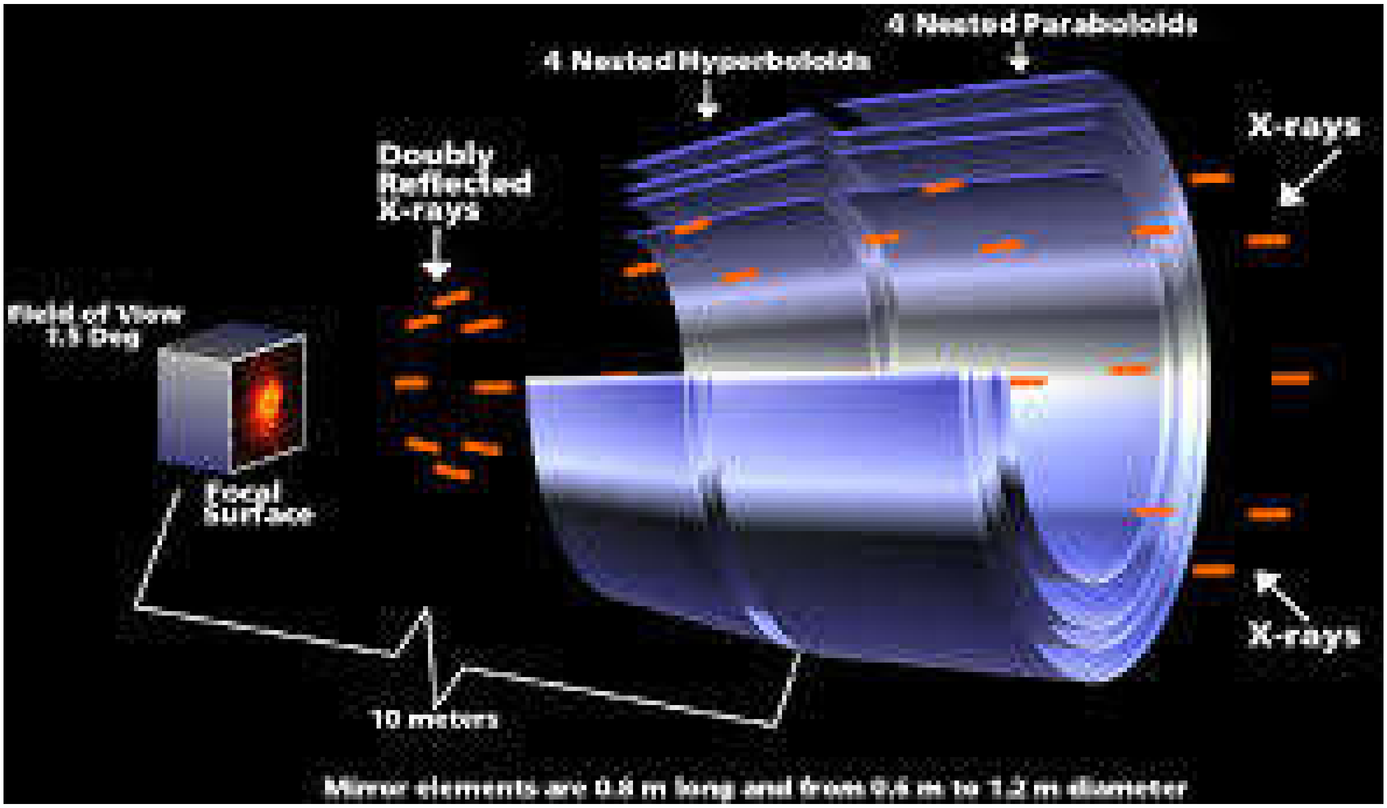


Illustration 20 : Pathways in an X-ray telescope (3D)

Let us see what that looks like in 3D. Here you see the telescope in action. If we had an ordinary mirror, it would not be able to obtain any X-rays. However, at grazing incidence, you can see that photons coming in all along the periphery of these mirrors can now get collected at our detector and the image can result. Before the advent of these mirrors though around 1980 was the first time, we were able to use them.

What did we do? How could we collect the light?

Well, things were a lot simpler then. Even though we could not get an image, we could at least figure out how or where something might be coming from, in the sky with very primitive means. What we had were devices like this. All this is a paper towel roll. Now imagine that you have a retina, some means of recording photons but you do not have a lens that allows you to focus your light.

How can you figure out where anything is coming from?

Well, it turns out that in this primitive situation, what you can do is just hold this thing up to your eye, and just kind of cruise around.

You want to see what is light?

Just look for light. You are not going to be able to see any objects because you do not have a lens, but as you cruise around, things are getting brighter. Things are getting, oh! There is a source of light! Okay? In addition, that is the way we used to do it in the old days of X-ray astronomy in the 1960’s. It turns out that this was a big problem for us, because these X-ray sources were sometimes buried in a myriad of stars, any one of which could have been the X-ray source. We just did not have accurate enough positions to do the subtle things that we now can do in understanding where these X-rays come from.

What you see in front of you is a square part of the sky that has been imaged by the Palomar Telescopes, and it is part of their Palomar Sky Survey. One on the side is about all we could do without the advent of X-ray mirrors. Our collimators were primitive, and one was really doing well.

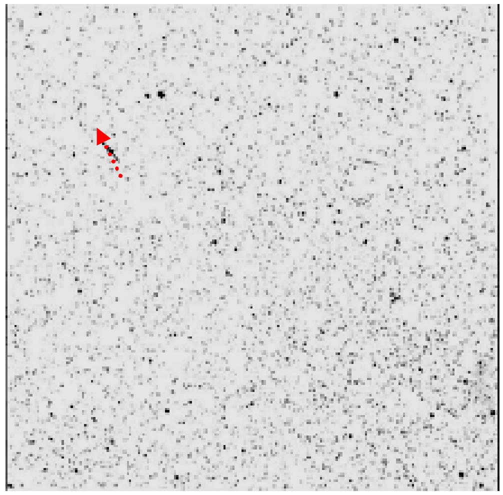


Illustration 21 : Palomar telescope image (1° angle)

Look at this. This is an image of the region of the sky that contains Sco X-1, the brightest X-ray source in the sky. Now it is apparently the brightest X-ray source in the sky because like the sun, even though the sun is the brightest thing that we see, the sun is not the brightest thing out there. This similar in the case of Sco X-1 it is the brightest thing that we see, but as we shall find out later on in this course, there are other objects that emit X-rays even more prodigiously than Sco X-1. However, look at this image.

Hundreds and hundreds and thousands and thousands of stars, and which one is the X-ray source?

Right over here by the arrow, this tiny dot that seems to be so inconspicuous is the source of the greatest amount of X-rays that we get every second from the sky, in the celestial realm of the stars. You can imagine the difficulty in picking this object out without having the means of imaging X-rays, and being able to pinpoint this tiny spot that turns out to be Sco X-1.

Well, now that we understand a little bit more about the way X-rays can be imaged in our telescopes, it is time to move on, and explore how our eyes perceive these images, and what our eyes tell us about them.

4 The Perception of Images

'Seeing is believing' is one of the trivialness phrases in the English language, and it turns out that the way our eyes perceive information is quite fascinating and a bit complicated. Therefore, it is not just enough to say 'seeing is believing,' especially when it comes to something like an image that might be generated by an X-ray satellite.

Our story begins over 2,100 years ago when Hipparchus roamed the earth. Now, it probably is just a continuation of a saga that began even earlier, but because we have no records of anything, and that unfortunately is due to the burning of the Alexandria Library, our first record really is an indirect one from Ptolemy, who told about how Hipparchus developed a system to understand the brightness's of stars.

What Hipparchus did is he assigned six levels of what he called magnitudes to the just noticeable differences between brightness's of stars in the night sky. Much to the consternation of countless generations of astronomy students since, he assigned the smaller number, like the first magnitude, to the brighter stars, and the faintest magnitude, sixth magnitude, was for stars that were much dimmer. Therefore, we have to understand that the magnitude scale varies inversely with the brightness of your object: the brighter the object, the smaller the magnitude. Not a real problem, not a showstopper, but just something to consider for the future. Interestingly enough, even though it was 2,100 or 2,200 years ago, this magnitude system of just noticeable differences is been propagated throughout, and is still used by astronomers today with certain refinements that we will discuss. Basically, the refinement that we have done is we have assigned, more or less arbitrarily based on Hipparchus' result that any change of five magnitudes in an object's brightness corresponds to a factor of 100 in actual brightness.

$\Delta m = 5$ corresponds to a factor of 100 in brightness. We will discuss this matter shortly. However, before we do that, we have to fast forward to around 1850, which, coincidentally or maybe not so coincidentally, correspond also with the advent of photography. In the 1850^{s}, a German physicist, Gustav Fechner, found out that he could assign a just-noticeable difference to a particular stimulus, only if that change in the amount that was necessary to produce that just-noticeable difference was proportional to the stimulus itself.

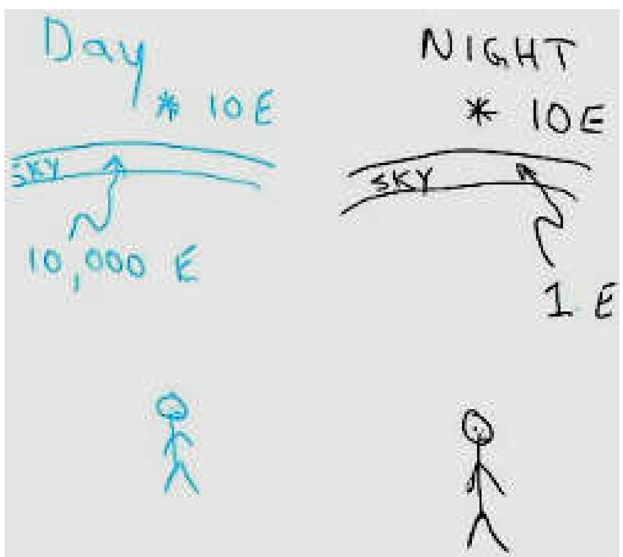
Let us think about that for a second. What that, basically, means is, that if you are confronted with two lines, drawn on a piece of paper, one line is very small, and the other one is just a little bit bigger. When that line is small, you can actually detect a very small change in that size of the line. However, if you have a very large line drawn on your paper you will be very hard put to be able to distinguish that line from one that is just a minor difference bigger. In other words, the amount of change in the length of the line or the amount of change in the brightness of the star that you can detect, as a just-noticeable difference, is proportional to the length of the line or the actual magnitude of the star itself. Now, the consequences of this are astonishing. One of the things that this implies, unbelievably, is the fact that the stars come out at night.

How can that almost silly statement of fact mean something as far as our understanding about the way the eye functions and behaves?

In order for us to do that we have to look at the circumstances surrounding looking at a star, both in the daytime and the nighttime, and in order to do this we are going to assign a new unit of brightness. I am going to call this unit of brightness an Eliza in honor of my granddaughter's first birthday that just occurred.

Therefore, here is the situation. During the daytime, we have a star and we have a sky. The starlight has to travel through the sky to get to us, and when we are looking at the star, we are looking at the superposition of the star's light and the sky's light. The same thing is true during the nighttime. We have a star, which we will think of as the same star, and a sky that is significantly darker than it is during the day. Therefore, let us assign brightness or a set of brightness's to these objects.

Let us suppose that at nighttime, we are looking at a star whose light has a brightness of 10 Eliza's, and the sky has a brightness of one Eliza. During the daytime, the situation is similar in the sense of the star still has a brightness of ten Eliza's, but now our skylight we will say arbitrarily has a brightness of 10,000 Eliza's. Therefore, it is 10,000 times brighter in the sky during the daytime than it is at night.



Now, we just develop a very simple table consisting of daytime and nighttime. We are going to imagine that we look at the star and the sky.

What happens?

During the daytime, when we are looking at the star, we are seeing the brightness of the star itself plus the brightness of the sky. When we are looking off the star, we are going to see just the sky light. During the nighttime, when we look at the star, we see the starlight plus the skylight.

	Day	**Night**
On star	10,010 E	11 E
Off star	10,000 E	1 E
Δ	**10 E**	**10 E**

They are the same. What that means is that if our eyes actually responded to differences of brightness's, we would be able to see the stars during the day. We do not, and what that means is our eyes do not respond to differences of brightness's, they respond to multiples of brightness's. Let us see how that works.

Imagine you have two stars. The first star has a magnitude of one, and the second star has a magnitude of six. It turns out that a difference of magnitudes = 5 correspond to a factor of brightness; the brightness of star 1 over the brightness of star 2 = 100. The first magnitude star is 100 times brighter than the faintest star that the eye can see.

$$m_1 = 1$$
$$m_2 = 6$$
$$\Delta m = 5 \Rightarrow \frac{B_1}{B_2} = 100$$

For each five magnitudes difference it is another factor of 100. Therefore, for instance, if we were to compare a first magnitudes star to an eleventh magnitudes star:

$$m_1 = 1$$
$$m_2 = 11$$
$$\Delta m = 10 \Rightarrow \frac{B_1}{B_2} = 10{,}000$$

What this means, and the consequence of this is astonishing, is that our eye has a tremendous dynamical range. We can perceive with our eyes about, more or less, 25 magnitudes of differences in the sky. That corresponds to an astonishing 10 billion times from the faintest object that we can perceive to the brightest object that we can perceive. Comparing that to the best CCD's that we have for our digital cameras, which only have a dynamic range of maybe 10,000, we are able to look at objects in the sky about a million times more sensitively than we can with an ordinary camera or any other type of recording device. That means that our eyes can really perceive a tremendous range in brightness. Not only that, that seems to apply to stimuli that are auditory, things that you can hear, although it is not quite as good for your ear as it is for your eye, and this is what Fechner found out in the 1850^{s}.

We can summarize that very easily. The change in a stimulus that is necessary to produce a just-noticeable difference in perception is proportional to the stimulus itself. That means that the change of brightness that we can perceive as a just-noticeable difference is proportional to the brightness and things like that. Change in a sound intensity proportional to the intensity itself. What that means is that our eyes are logarithmic detectors. This is why you should study why logarithms exist. This is the description of the way we perceive radiation.

Now we need to look at X-ray images, and, again, see how these considerations apply to objects that we really cannot see. We do not have any sensitivity to X-ray light at all. Therefore, when we get an image in our telescope we have to create some sort of color map. Right off the get go this is going to be a false color map, because there are not any colors that correspond to X radiation that our eyes can perceive. We have to make the invisible visible, and how we do, it is somewhat arbitrary, very interesting.

Afterwards we will come back and say, is seeing believing? If it is, then what actually are we seeing in terms of an X-ray image?

Therefore, from here we have to go to our trusty piece of software, DS9, and look at an image of an X-ray source.

5 Introduction To DS9

Now it is time for us to get our handy-dandy, nifty piece of software that will allow us to explore the X-ray universe in depth. The name of this piece of software is **DS9**, and it was developed by the Smithsonian Astrophysical Observatory to analyze X-ray and other types of astronomical objects. It really is a neat program, and I am sure you are going to enjoy using it.

I often think of this program as being something like a Photoshop on steroids. It is also free, which is nice, and you can get it in the following manner. Downloading DS9 is really a snap, and that is what we are going to do next.

All you have to do is go to this website. If you do not want to take the whole thing down by hand, probably the easier thing to do is just go into Google and enter SAO DS9, and the search will take you to the same place.

Depending on what version of an operating system you have for your computer, you can download the appropriate version of DS9. You will see it says Windows 7. It turns out this will work fine for Windows XP, and should you be unfortunate enough to be using this particular version of Windows, namely Windows Vista, it will also work very well for that. For your Mac operating system even though there are bunch of possibilities above. I would recommend that you try downloading MacOSX 10.6 first, because Apple in, again, its infinite wisdom decided to eliminate a particular part of their system that would ordinarily be used for the latest versions of DS9. In any event the functionality between the Mac versions and the Windows versions and, of course if you are a Linux buff, there it is for you. I am sure I would not have to tell you any more about how to deal with Linux if you are already using it, and you will find that the functionality for these particular programs are identical, no matter which operating system you choose.

After you download DS9, if you launch it, you will see something like this.

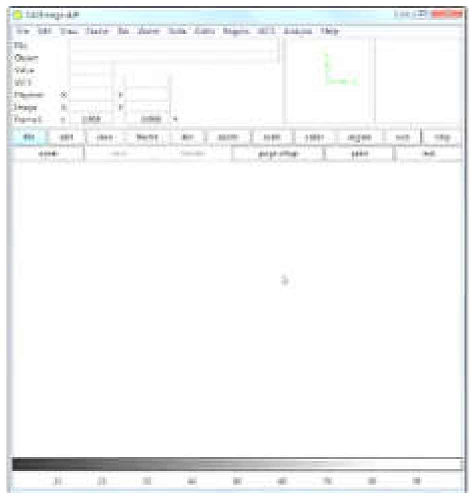


Illustration 22 : DS9 start screen (Windows version)

This is the Windows version, and you see a blank screen here, in which we are actually going to end up with our astronomical images. You will see a menu across the top with various possible things that you can do with DS9 that we will be exploring. The Mac version will look very similar, except that all of the entries to the possible analysis sit on top of the screen, separate from DS9, which, again, has the same area that we are going to load images into. Because of the fact that it is disconnected, I have chosen to use the Window's version, which, once again, keeps everything together as the demonstration example throughout this course. In any event, you will not have to worry about this, because everything is, more or less, identical. If there are any differences between these two things, I will point them out as we go along. That is, basically, all there is to download DS9.

What I am going to do in the next short segment is sort of try to whet your appetite for seeing what some of the possibilities are that you can utilize this great program for. We will have an extensive DS9 smorgasbord starting next, but in the next couple of minutes, I just want to take you through some of the more elementary things that we can do using this program. Therefore, get DS9, and get ready to explore some very interesting astronomical objects in our universe.

Well, now that you have DS9, you are going to want to see how to use it. Next, we will have an in-depth tutorial on all of the things that DS9 can do. Nevertheless, I thought it would be interesting for you to finish out this lesson with just a general broad overview about the structure of the software, and some of the neat things that you can actually do with it. Therefore, let us go over to our screen, and see what DS9 is up to.

We open DS9, and usually the first thing that you are going to want to do is go to the menu bar. Under *Analysis* you are going to scroll down and click on the *Virtual Observatory*. This will bring up a window that allows you to connect to the hundreds and hundreds of observations that CHANDRA has made over the years.

5.1 ATTENTION!

News Flash! We interrupt this broadcast to bring you a special bulletin. DS9's 'Virtual Observatory' needs to have a parameter set in order to function properly. It is easy, and here is how to do it for both Mac and Windows systems. If you have a Macintosh, this is what you do. When you start DS9, you go to 'Analysis', click on the *Virtual Observatory*, and before you check *Rutgers Primary MOOC X-ray Analysis Server* just make sure that the radio button that is says *Connect To VO Servers through the remote Web Server* is initialized. When you do that, DS9 will function properly.

If you do not want to do that, every single time you initialize DS9, every single time you use it, you can change in your *Preferences* a parameter that allows you to do it automatically, and you do not have to worry about it anymore. The way you do it is as follows.

You go to SAOImage DS9 icon in your top menu bar, and click on *Preferences*. When you do that, you will see a dialogue box, and one of the possibilities under preferences is *VO*, Virtual Observatory; click on that. When you click on that, you can then enable your connect using *Web Proxy radio button* over there, and after you click *Save*, you will then be able to save it. That is it.

For a Windows machine, it is almost identical. You go to *Analysis*, click on *Virtual Observatory*. Then you get your dialogue box, and before you click on *Rutgers Primary MOOC X-ray Analysis Server* make sure that you click on the radio button that says *Connect Using Web Proxy*. If you do not want to do that every single time you start DS9 for this course you can change the parameter in your *Preferences*, so it will do that automatically. The way you do that is by going to *Edit*, *Preferences'* Click on it, you will see a dialogue box, and you can select the *VO* for Virtual Observatory. When you do that you will get another box, and you just make sure that the little radio button that says *Connect Using Web Proxy* is enabled. You save it, and you are done. That is it, back to our regular programming.

First thing you are going to do is connect to the *Rutgers Primary MOOC X-ray Analysis Server*. Make sure that you click on the radio button that says, *Connect Using Web Proxy*. When you do that you will get another screen that now lists all of these observations. There is a listing of hundreds and hundreds of observations that have made with the satellite. In order to see what some of these things look like, we are going to click on the first one, *ACIS Observation of CAS A*.

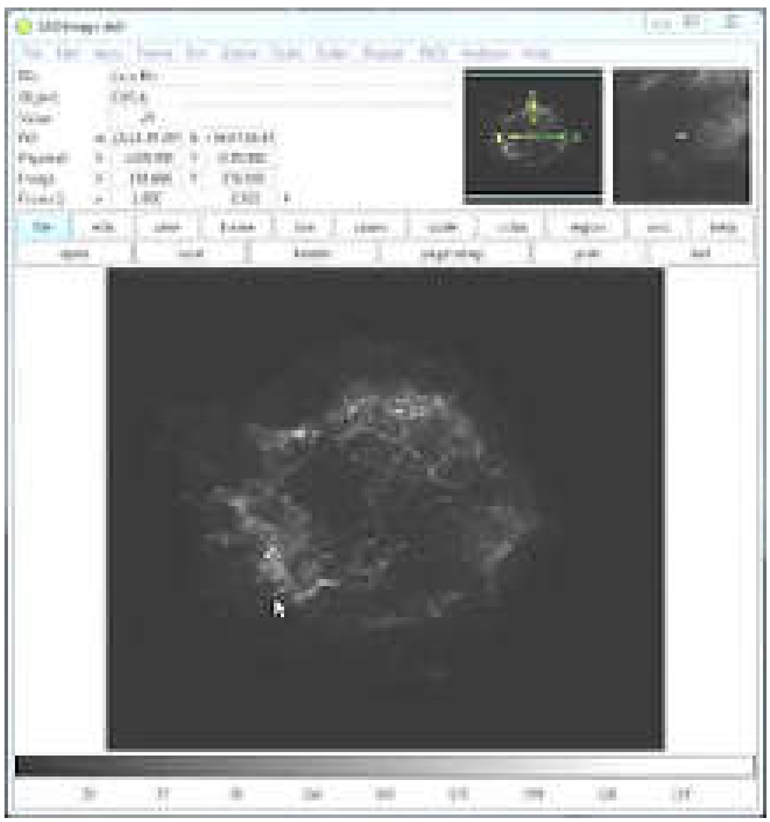


Illustration 23 : DS9 image: Observation of CAS A

Now you see immediately an image is loaded into our viewing area. We can change, for instance, its color by selecting different color schemes, and doing all sorts of interesting kinds of displays in that way. In addition, we can change something that has called the scale. Going to select the *Square Root Scale*, we will talk about that in a later lesson. You can see that this display now changes, and you can look at this particular object, which is a supernova remnant, in its entirety. Notice as you cruise around with your pointer, many things are changing in the informational area near the top left of your window. You see something called *Delta* and *Beta*, which is the position in the sky. You also see the actual pixel that is being looked at or pointed to, and you can see that more clearly in a magnification box that is at the upper right hand corner of your main window. In addition, what you will see as you cruise around is the value of the intensity at the particular point that the arrow is looking at, and you can see that value change as you go from one place in the supernova remnant to another.

Now, it is hard to select a particular point using the mouse. Things kind of jump around a little bit, but what you can do is, for instance, you can click setting down a region there. We will talk about regions, and that is going to be the area in the object that you are actually going to examine the data for. If you click again, after clicking once, you can see that now you have selected that region, and there are four little handles that allow you to change that region wherever you want, and you can go up or down, one pixel at a time, by just using you are up and down arrows on your keyboard. Therefore, notice what happens in the informational box when we do this. The value changes, meaning the brightness of the supernova is changing as we look at different parts of it. You can see in the magnification box what you are actually looking at magnified, so you actually can see the pixel structure. You can see the position in the sky is changing; it is *Delta* and *Beta*. The actual pixel number that identifies where we are in the actual photograph or image also changes. Therefore, you can use your up and down arrows, left, and right, to move one pixel at a time.

Now, if you accidentally put down a region that you want to get rid of, all you have to do is select that region by clicking again within it, and hitting the delete key. Boom! The region is gone. You can still pan up and down. Now is interesting, this little tiny white dot, almost one pixel in size, actually a couple of pixels in size, but definitely tiny, and geez, it looks really close to what might be the center of this object. We are going to have more to say about that as time goes on. Now, in order to see what the values of the brightness's are in the regions surrounding where you are pointing, you can actually go to *View*, and have the horizontal and vertical parts of the image explicitly shown to you. Watch what happens when you go back into the area that is denoted by the supernova remnant. You can, for instance, set down a region, go back and forth, and look at a slice, through the supernova remnant, both vertically and horizontally; things change as you move one pixel at a time.

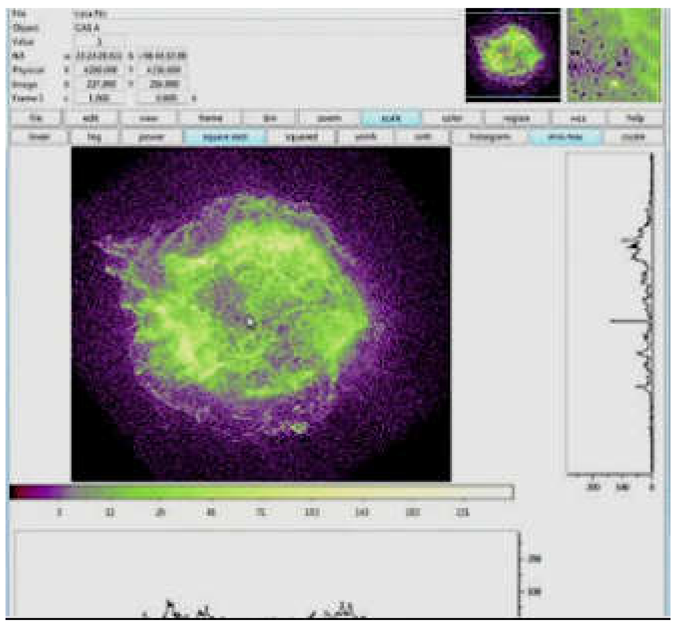
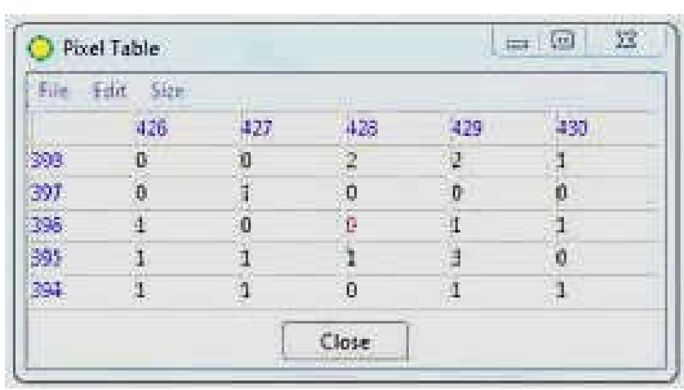


Illustration 24 : DS9 Image (Intensity of one pixel)

Let us go back to this central point. Now, in order to see what the actual values are of the region surrounding it, let us go to *Analysis,* and look at the *Pixel Table*. You get a little box, which gives you, along the top and left side of that box, the actual image pixel numbers. You can actually go back and forth, if you want, by one pixel at a time, to see what the intensity of the supernova is, in this particular case, very close to the center of the remnant.



Pixel Table

File Edit Size

	426	427	428	429	430
398	0	0	2	2	1
397	0	1	0	0	0
396	1	0	0	1	1
395	1	1	1	1	0
394	1	1	0	1	1

Close

Illustration 25 : DS9 Image (Pixel table)

Let us see how close it is to the center, really?

Well, just grab one of those little handles, and drag our region out to make it bigger. Boy, it really does look pretty close to being in the very center of this big blob in the sky.

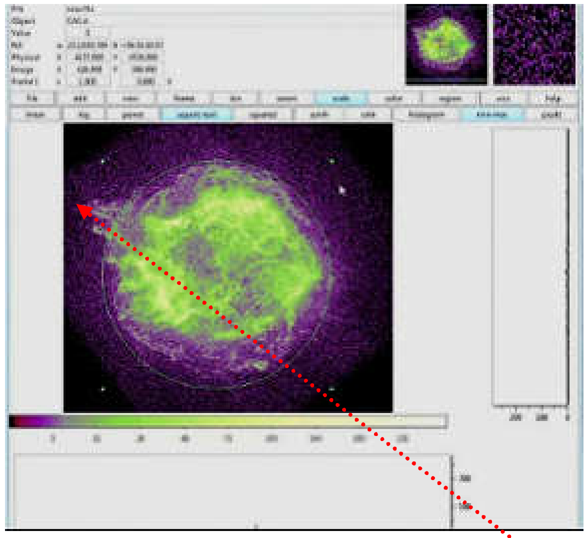


Illustration 26 : DS9 image (Intensity of a whole region)

However, there is some other stuff, like what is going on here?

That does not look like its part of some kind of spherically symmetric object. These are all things that we will explore in the future, and this gives you at least some idea about what can be done using DS9. To look at another source, let us do the following. First, let us get rid of our Pixel Table; let us also get rid of our horizontal and our vertical graph. Let us load a different observation. What we are going to do here is instead of looking at CAS A, we are going to look at another supernova remnant, called Tycho. We will load *Tycho* into our observation box; *Color*, we will, I guess, leave at *HE*, and *Scale*, well, let us see what linear looks like. That looks good. Okay, now notice that there are these kinds of like gaps in the data.

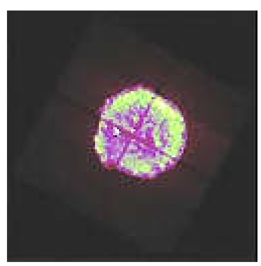


Illustration 27 : DS9 image of Tycho with X pattern from CHANDRA

That is actually a reflection of the chips in the CHANDRA satellite, and the fact that these chips are located side by side, there are some parts of the sky then that fall between the chips. Therefore, sometimes you will see these X types of patterns that really do not mean anything as far as the actual X-ray source is concerned. Now I want to show you something interesting. Let us go back to *Analysis*. Now we are going to look at an *Image Server*. This is a set of data that actually consists of other types of optical or radio images of the same area in the sky. For instance, we scroll down to *NRAO NVSS* and click on that. What we end up with is another little window, and it will now allow us to retrieve that part of the sky that corresponds to the *Delta* and *Beta*, or the position coordinates of the Tycho supernova remnant. Therefore, if we click on *Retrieve* you now see a little box. That is the radio image of the exact same part of the sky, as we see on the left.

Illustration 28 : Radio image of Tycho

We can do something even neater than just displaying it. I am going to click on the left frame, which is our original X-ray image. Now, if I go to *Frames* and scroll down to *Match Frames*, and I click on *WCS*, which is World Coordinate System, boom! Look at what happened to our radio image. It got slightly larger, and it got slightly larger in exact proportion to the size of the X-ray image.

Now we are seeing the exact same areas in the sky at exactly the same magnification. Now we can do something that is even more interesting. If we go to *Edit* and change our Pointer to a crosshair, now we have a set of crosshairs that can link up the radio image on the right with the X-ray image on the left. We can lock the two together. If we go to *Frame> Lock> Crosshairs*, now we can cruise around one of those images, picking out regions, and seeing exactly what corresponds to that part of the image in X-rays, in the radio regime. Therefore, you can cruise around the entire area, and select out regions of the sky that might be of interest to you.

Now, one of the things you will notice right away is that this radio image looks blurry. It is not blurry; it is just the fact that radio waves have much longer wavelengths than X-rays. Because of this, it is just an unpleasant fact that you do not get the same types of resolution for your images.

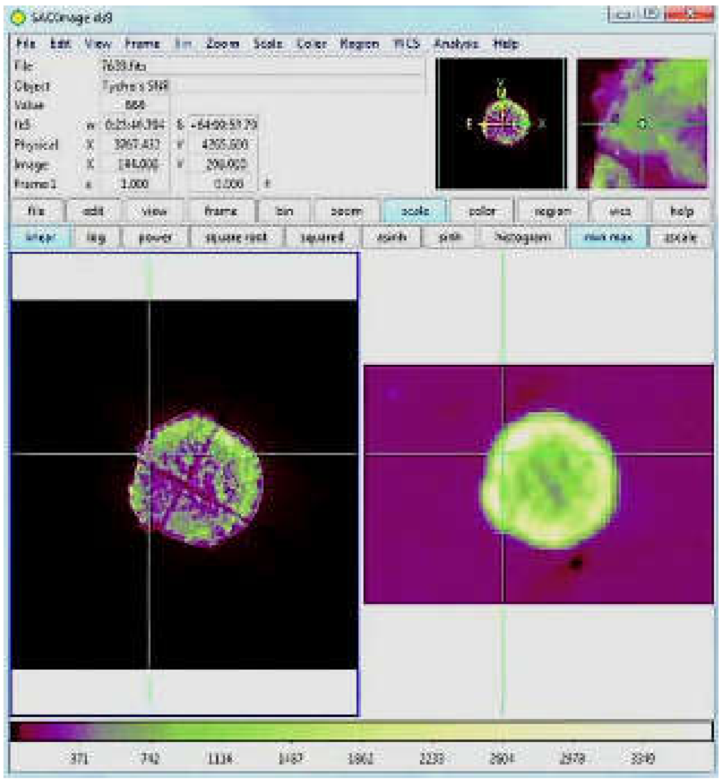


Illustration 29 : X-ray and radio image of Tycho (scaled)

Things do not look quite as good in some radio images, as they might have look in some X-ray images, but radio astronomers have many tricks up their sleeves, and they can use interferometry to make these radio images appear pristine and accurate. This is really our first cut at what DS9 can do. I hope you will use DS9 on your own. Starting next, we will have an in-depth tutorial about what this nifty piece of software can do for us.

Basic Astronomical Data And A DS9 Smorgasbord

1 The DS9 Smorgasbord

At this point, please watch "Analyzing the Universe002.mp4"

Video 2 : DS9 Smorgasbord

2 Lies, Damned Lies And Statistics

Today I want to talk to you about how science answers questions. We all want the right answers.

Should I prepare for rain today? How can I deal with my boyfriend or girlfriend? Should I go to the ball game or the concert tonight?

Every day we face myriads of circumstances for which we need answers, the right answer.

2.1 Boundaries

Sorry, but science never can tell you the right answer. All we can do is giving you a probability that an answer is correct or not. What this means is that we live in a statistical universe. If the universe is statistical by nature, and we now have quantum mechanics to back up that claim, it may be that fundamentally a 100 % true deterministic answer does not even exist. In this very real sense, the universe with its constituents is not a machine, but an indeterminate process. Even if it is indeterminate, it is not a free for all, but constrained by certain boundaries. It is these boundaries that physics wishes to explore, quantify, and refine. Therefore, we have a problem on our hands.

If there are three kinds of lies: lies, damned lies and statistics, how are we to proceed? Incidentally, that phrase is often attributed to several people, among who are Mark Twain and Benjamin Disraeli. The fact of the matter is that the only way we can find out whether we are dealing with lies, or damned lies, is through statistics. The way it works is as follows.

If a theory predicts a phenomenon that is not observed, we can rule out the theory, but if it does accord with the data we have, all we can say is that the theory is consistent with the data on hand, not that the theory has been proven correct. In fact, we can never prove a theory correct. What this means in practice is that the most important part of any scientific experiment is the probable error associated with the measurement. It is more or less the wiggle room that we give a measurement, by how much our measurement might be different if we did the experiment repeatedly.

As a concrete example, let us image we are trying to measure the length of a dining room table. We get out our trusty old stone-age tape measure, and do an experiment: Measurement 1: 260 cm.

What is the experimental error that we can estimate from this measurement? You might think nothing, since we have nothing to compare it to, but wait. If we look at our stone-age device, we see that it is very crudely made with big unmarked segments and thick lines marking the intervals. We can estimate something called a **systematic error** at say 10 cm, but we are not satisfied with that. Therefore, we make more measurements: 250 cm, 260, 250, 270, 260, and 100!

100 cm?

What happened? Do we really think that the table length is variable? It might be, but at first glance, it appears we have made what we call a blunder. If we use that 100 cm measurement in our computation of an average length we will throw off everything, but if we suspect a blunder, we need to track down its source if possible. Using the six supposedly valid measurements, we can obtain a sample average of 258 cm. Now we can ask, "What is the experimental error associated with this determination?" In other words, how close to 258 cm would you expect each measurement to be?

Clearly, we must compare our sample average with the individual measurements we already have. In addition, we sense that the measurement that is smaller than the average should count equally with a measurement that is larger. Therefore, we better square things first, and then take the square root in order to avoid - signs that would be associated with measurements that might be smaller than average. We expect that we need to take the following quantity.

$$\sqrt{\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2}$$

Equation 1 : Standard deviation

In other words, for each of our *N* measurements we compare the actual measurement, x_i, with the mean of all the measurements, $\bar{x}$, and square it. Then add all *N* results together, and take the square root of the whole shebang.

However, clearly something is missing here, because larger samples of measurements should not imply a larger error. Measurements have to be worth something; therefore, we sense that our estimate of standard deviation should include some factor of $^1/_N$.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2}$$

In fact, it turns out that this quantity, usually designated as σ (sigma), is equal to our previous sum, but divided by the square root of *N*. In essence, we are taking the average value of the square deviations from the mean. Remember that you need a minimum of two measurements to get any average value. This leads to the refinement of our equation as follows.

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2}$$

Equation 2 : Sample standard deviation

It is the same as before, except it has *N - 1* instead of *N* under the square root. The value of this quantity, σ, associated with a mean value can be shown to have an astonishing property. That 68 %, or about $^2/_3$, of all measurements you can possibly make, even into the future, will fall within ± 1 σ of the mean, as long as the properties of the phenomenon have not been altered.

Summarize

±1 σ ⇨ 68% of all data points

±2 σ ⇨ 95% of all data points

±3 σ ⇨ 99.7% of all data points

Illustration 30 : Influence of σ

It does not matter what you are measuring. You could be interested in the height of 25-year-old women in Borneo, a comparison of daily maximum temperatures of two cities anywhere in the world, measurement of returns on investment versus risks in financial markets, analysis of statistics of scoring in sports. All of these, basically, use the same ideas presented here.

However, if the phenomenon has changed, or a new phenomenon is somehow buried in the data, a smaller standard deviation will enable you to detect it more easily. Let us get back to our table and fast forward to the 21st century. New devices now allow us to obtain much better precision in our measurements. Using the same table, we may obtain the following results.

1	258.68 cm
2	258.62 cm
3	258.87 cm
4	258.89 cm
5	258.64 cm
6	258.65 cm
7	258.88 cm

You look you at these numbers closely and say, hmm. Are we seeing something significant in the fact that the numbers seem to cluster around 258.65 and 258.85? Maybe, maybe not, but we pay attention to this detail, and then find out with additional measurements that we have obtained the higher numbers when the temperature of the room is significantly higher than when we look at the lower values. We have discovered something.

The table is changing its length in response to a temperature change in its environment. Our measurements have revealed the thermal expansion of the table. Something we had not anticipated, perhaps, and X-ray astronomy, as we shall see, is filled with surprises of this sort. I am sure your life is filled with them as well. When have you thought that you were exploring or answering one question, when in reality you were finding out something quite different instead?

We now shift gears and look at a hypothetical astronomical example. In this case, our determination of the standard deviation, or uncertainty in our measurements, is even easier to obtain than our result for the table length. This is because in certain situations, which fortunately include most astronomical observations, a very simple result ensues concerning what we might expect from a measurement of the brightness of a cosmic X-ray source as a function of time. The idea is as follows.

Let us suppose you have a random process, such as the emission of light from an object. We know that when an electron changes its energy from within an atom by jumping from one level to another, it is accompanied by the emission or absorption of a photon. We know that it is random in the mathematical sense, because we can never know exactly when this will happen, but it will probably happen in a given certain time period. If it happens to lots and many electrons lots and many times, we will get lots and many photons into our cameras or detectors.

Let us suppose, to make this concrete, we observe a source for 10 min and count 21,262 photons. We sense that if we were to do this measurement repeatedly, we would not get exactly 21,262 photons repeatedly, even if the source were unchanging. The randomness of the process ensures this. In these circumstances, there is a simple way to estimate what the probability is of getting another result similar to, but not identical with our first trial, if we were to repeat our measurement. We simply take the square root of the number of photons observed, and that represents the range, ± from our observation that we would expect to see $^{2}/_{3}^{rds}$ of the time, if we were to do the observation repeatedly. If we consider our original observation, we would expect to observe 21,262 photons ± 146, about $^{2}/_{3}^{rds}$ of the time, if we were to repeat the experiment repeatedly.

Why?

146 is approximately the square root of 21,262. The number 146, once again, is the standard deviation of our observation.

In astronomy, however, just raw numbers of photons are not particularly interesting. We are more interested in rates. How much energy is emitted per second, or how many photons are detected per second during any given observation? Let us see how this plays out in practice.

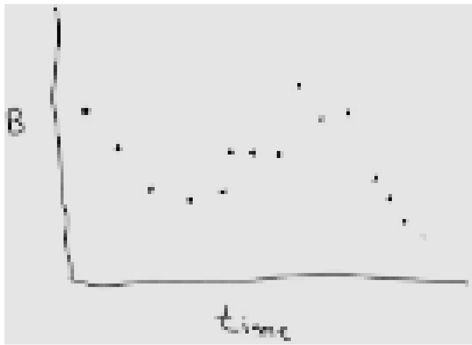
Let us imagine that we have 100 photons in 10 s. Our expected range, or in statistical language our standard deviation, will then be 100 ± 10, because 10 is the square root of 100 over the 10 s. This translates into a rate of 100 counts over 10 s ± 10 counts over 10 s or 10 ± 1 $^{count}/_{s}$.

Let us imagine the same source, which is assumed unchanging, but now we observe it for 1,000 s. In other words, our observation is 100 times as long. Since we get 100 counts in 10 s, we would expect to get 10,000 counts in 1,000 s. Therefore, we would expect to have 10,000 ± 100 counts in our observation. Our rate then would be:

$$\frac{10{,}000\ counts}{1{,}000\ s} \pm \frac{100\ counts}{1{,}000\ s} = 10 \pm 0.1\frac{counts}{s}$$

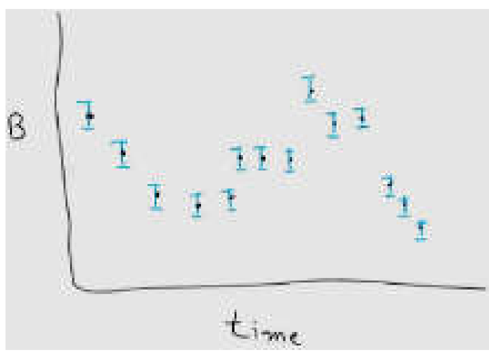
Notice: We needed 100 times more data to get our standard deviation down by only a factor of 10. What a bummer. As you see, it can be slow going and sometimes very expensive to get better and better results, but it is the reason why scientists are always asking for more data, better detection instruments, and bigger telescopes. We will explore this important issue in greater depth later when we talk about clocks in the sky, but for now we will just state that the size of the error bar, or standard deviation, may play a decisive role in what we can legitimately say about an astronomical source.

Consider the following hypothetical data points measuring the brightness of an object versus time. What we are going to do is we are going to plot the brightness of a source versus time, and let us imagine that we have the following points on our graph, something that looks like this.

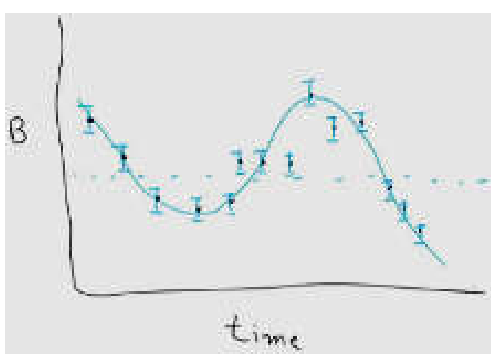


These are our measurements as a function of time of this source of light. Now we ask a simple question, is this source varying?

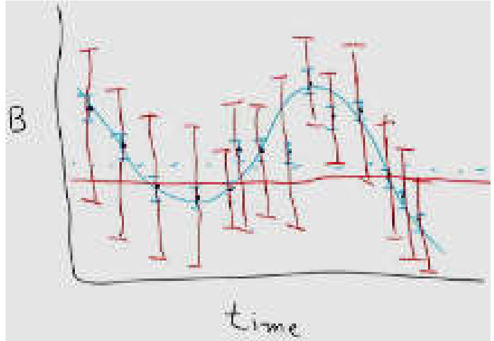
It depends on the size of the error bars. With a small σ, we are more or less forced to connect the observations with some kind of variable curve. Let us look at that. Let us just look at what would happen if we have very small error bars attached to which of these points.



You can see that it is impossible to fit an ordinary, non-varying line through the data that would meet our requirement that $^2/_3$rds of our data points are within ± 1 σ of that particular line. We are almost forced into drawing something like that.



However, this is not the case with larger error bars. Let us imagine that we have exactly the same data points, but now we have associated with each measurement, maybe because we are using a smaller telescope or our detectors are not as good or whatever, the same data have big error bars. You can see that it is quite easy to meet our requirement, more or less, of $^2/_3$rds of all of the data being within ± 1 σ of our mean by fitting a straight unvarying line through the data.



Therefore, you can see that the standard deviation σ is critical to our observation, and it will determine whether our scientific estimate of variability is a lie, a damned lie, or a legitimate statement of probable fact.

3 Atomic Spectra, The Fingerprints Of The Stars

I want to talk to you about some of the incredible things that we can tell from looking at the stars. It is truly astonishing that the feeble light from objects apparently so very dim can illuminate so brightly our knowledge of the heavens in so many ways. The story begins over 100 years ago when the world of physics was truly shaken to its roots by the discoveries of the quantum world. Several key surprises had fundamental implications for the study of astronomy.

The first surprise was the requirement of specific orbits for electrons as they traveled about the nucleus. Unlike planets, for example, that could orbit their stars at any distance quantum mechanics forbade all but a very specific set of distances for the electrons to reside in. Indeed, this understanding became a triumph as it explained with incredible accuracy the heretofore-mysterious occurrence of the dark lines in stellar spectra.

The idea is that in the case of planets, for instance, you have a sun, and you have planets going around the sun, but those planets could inhabit any region external to the sun. There was nothing to prevent Mercury, for instance, fundamentally from being in a slightly different position relative to the sun than it is today. That is not the case with atoms. In atoms, there are very specific, discreet levels that allow the electrons to reside in. Those discrete levels give rise to discrete energies corresponding to the change in those levels within the atom.

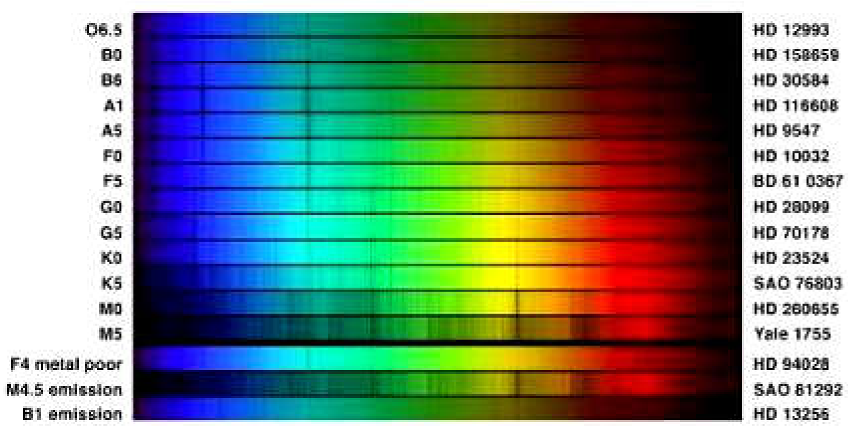


Illustration 31 : Spectra of different stars

What you see is the light output of over a dozen different stars. In the visible part of the spectrum, from red, the low energy photons, to blue, the high-energy photons, you can see many dark lines, which correspond to unique energies in the spectrum. These energies correspond to an electron in a particular atomic element or compound jumping from one discrete level to another. These lines give us valuable hints as to the chemical composition of the stars.

The way this mechanism works is as follows. Radiation comes from the center of the stars in all wavelengths, and they pass by an electron. The electron ignores all those photons except the ones corresponding to the energy necessary to jump to a higher orbit. Therefore, the situation might be that the blue photon continues on its merry way, the red photon continues on its merry way, but the electron, which then jumps up to a higher energy orbit, can absorb the yellow photon. This would correspond to an electron in the ground state going into, say, the second excited state, and that energy difference has to correspond exactly to the photon that has been absorbed by the electron.

What happens next is that the electron usually almost immediately falls back to the lower energy state and re-emits the photon. The electron can go back to his energy level and re-emit the photon, but here is the kicker. The direction of this re-emitted photon is random, and usually different from the incident direction. Furthermore, the electron may retrace its steps differently and re-emit different wavelength light altogether. In other words, the electron can, instead of jumping immediately down to the ground state, come down in a lower orbit, re-emitting a different photon, and then come back down to the ground state re-emitting yet another photon. In either event, the net result is that light of a specific wavelength is subtracted from the overall output, hence the dark lines in our spectrum.

Let us look at those spectra again carefully. Notice that not only are the lines different, but the overall output or color is different as well. The sample stars near the top have distinctly more blue light than those at the bottom, where it is clear that the red light predominates, and this is indignative of the different colored stars that we see in the sky. This brings us to the second part of our story, which was the discovery by Max Planck of the radiation law that governs how stars emit light, the so-called Blackbody Radiation Law.

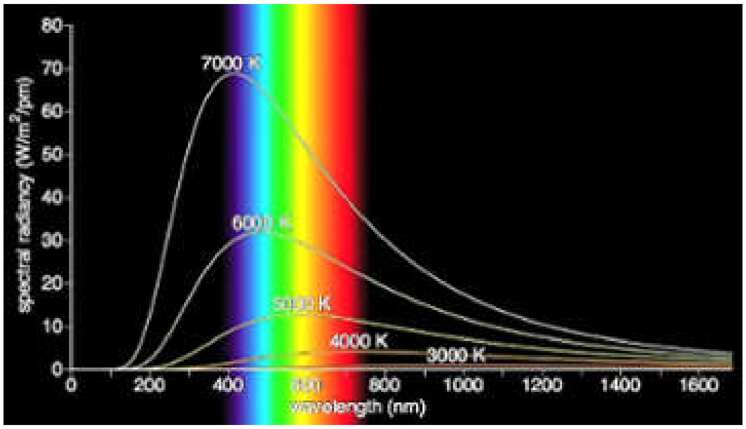


Illustration 32 : Blackbody radiation law

What we see here is that as the temperature goes up, not only does the total energy output / surface area element go up, but also the maximum of the radiation shifts towards the blue. The hotter stars around 10,000 K are much bluer than the cooler stars around 3,000 K. Incidentally the *K* is just another temperature unit based on the fact that 0 K corresponds to the absolute minimum possible level of atomic activity.

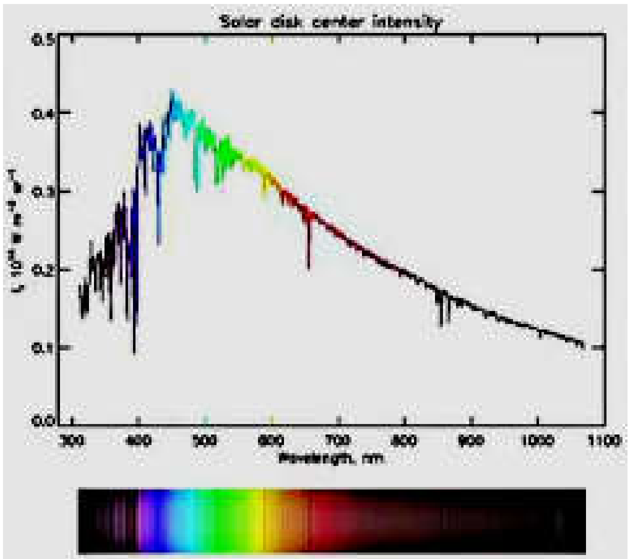


Illustration 33 : Solar energy spectrum

However, where are the dark lines? It turns out that these are departures from black body radiation. A true black body would have only continuous radiation, but when you put it all together, black body plus lines; you get something like this, which is the solar energy spectrum. It is very close to a black body with lots of dark lines superimposed on it.

In the late 1800^s Joseph Stefan deduced from experimental data, what the total radiation output must be for objects close to a black body. It turns out to be the following expression.

$$\sigma T^4$$

σ is a constant, based on thermodynamic considerations, and T is the temperature raised to the fourth power. Now, remember that our black body spectrum was the energy output for each surface area element of the object. In order to find out the total then we must take our expression and multiply by the whole surface of the star.

$$4\pi r^2$$

R is the radius of our star.

$$L_* = 4\pi r^2 \sigma T^4$$

Equation 3 : Total energy output of any blackbody radiator

That is the luminosity, or total energy output, of any black body radiator that is spherical in shape. The units on this luminosity depend on what units we measure for σ, and what units we measure for the radius. T is always going to be in K. For instance, if this was in CGS-units, we would have $^{ergs}/_{s}$, and r would be measured in cm. Now you can see the effects of the high power that luminosity has on temperature. A factor of 10 in temperature corresponds to a factor of 10,000 in luminosity, but if all we can see is the apparent brightness of the star in the sky, how can we find out the luminosity, or total energy output, that the star has? Only if we can find the luminosity we can deduce what the radius of the star is. Clearly, we need to determine the distances to the stars. Only with distances in hand can we deduce the actual parameters related to our observations of these faint pinpoints of light in the sky.

4 The Cosmic Distance Scale – Part I

Today I want to talk to you about measurement of distances.

Easy, right?

You just take a ruler, and see how far it is to somewhere else. One ruler length, two ruler lengths, three ruler lengths, four ruler lengths, and so on and so forth, but what about if you can't even get to the other place? Alternatively, if the distances are so vast, that ordinary rulers are impractical?

Such are the problems we have when we try to measure the distances to the stars. We need some sort of stellar bootstrap in order to extrapolate our earthly distance measurements into the realm of the cosmos. We begin, as we must, with our home, the Earth. As usual, our story begins with the Greeks, esp. with **Aristarchus of Samos**.

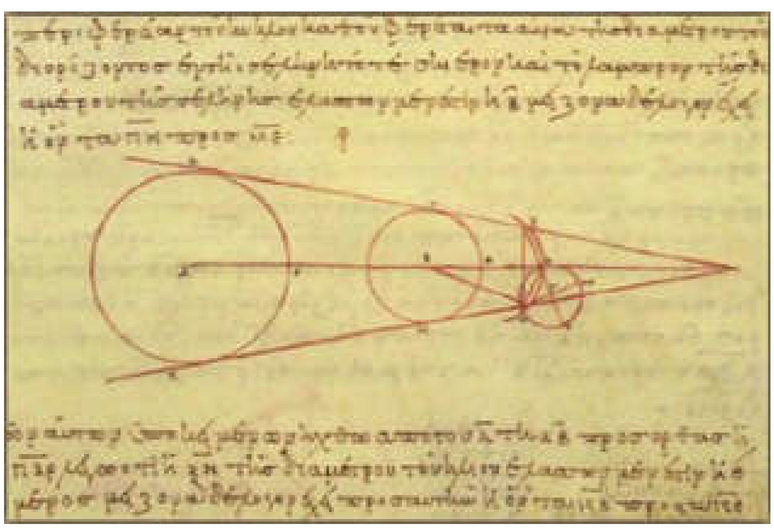
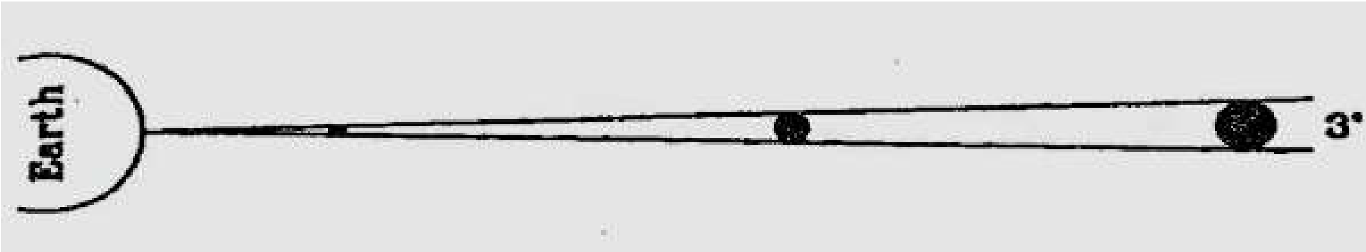


Illustration 34 : Aristarchus's working diagram

In particular, with Aristarchus of Samos around 250 BC, he concluded that the Sun, on the left, was much bigger than the Earth in the middle, and hence was most likely to be at the center of the Solar System rather than our planet. Let us dissect this diagram carefully and see how he did it.

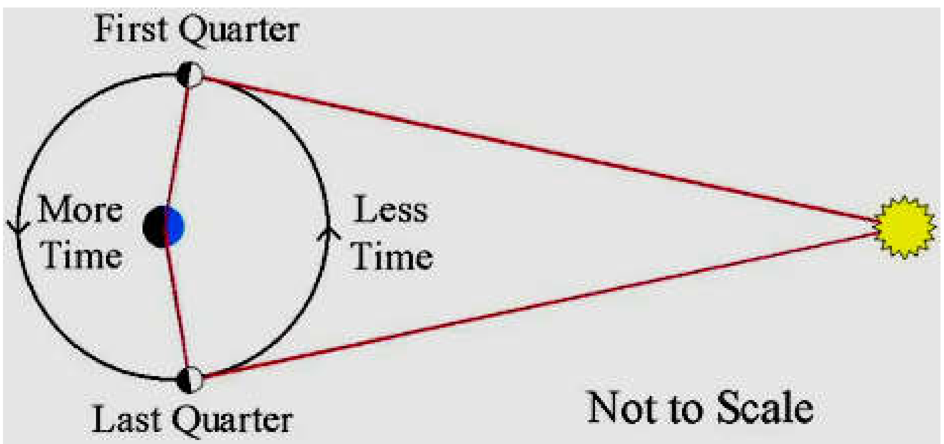
Our dilemma is that all we can measure is the angular size of an object in the sky, and sometimes not even that. This means that the size of an object is ambiguous.



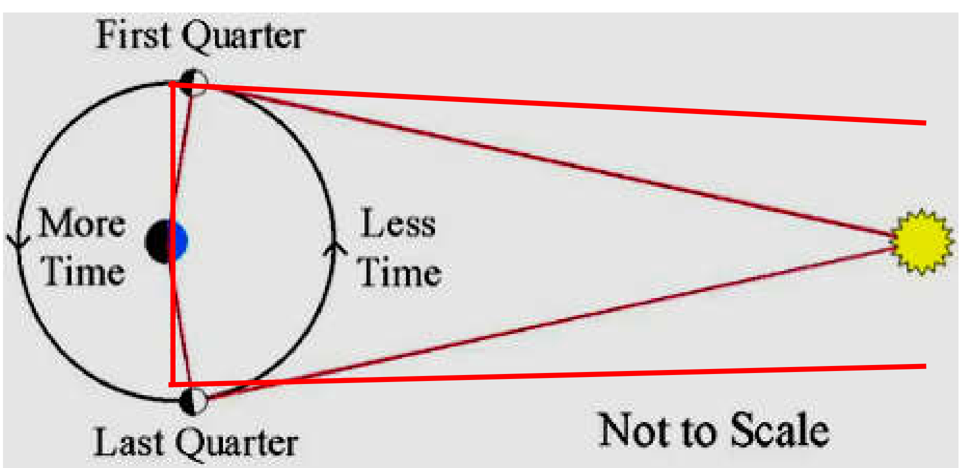
Let us consider this drawing. Here we have the Earth, and we imagine that we are looking out into space with a certain angular size. You see that the Sun, or the Moon, or any object with the same angular diameter can be either close and small, or far away and large, and still appear to be the same size in the sky. Therefore, our angle here is the same, but the object, depending on where it is, can be either large or small.

Aristarchus knew the angular sizes of the Sun and the Moon were the same; otherwise, we could never have a solar eclipse where the Moon almost exactly covers the surface of the Sun. He also knew that the distance to the Sun was much bigger than the distance to the Moon.

How did he know this? By realizing that the times from first quarter to third quarter of the lunar cycle was almost the same as from third quarter to first quarter. Let us look at this carefully.

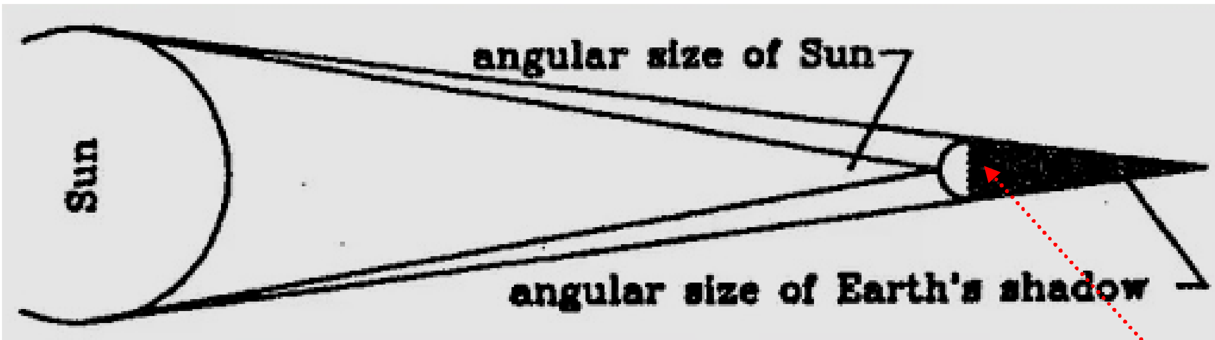


We imagine that the Earth is here, and that the Moon is going around the Earth in a circular orbit. Over here, we have the Sun, and for the quarter Moons what has to happen is the Moon has to make a 90° angle between the Earth and the Sun. If we have the Moon over here, this will be a 90° angle and we will see the first quarter of the Moon. When the Moon is down, about here, we will have another right angle, and we will see that this is the third quarter. Now it is pretty clear that for the Moon to go this way from first quarter to third quarter is going to be more time than for it to go this way from third quarter to first quarter. Note that as the distance to the Sun increases, the differences between the 2 arcsec of the circle become smaller. Let us see what happens.



If we put the Sun much, much further away you can see that the rays of the Sun will come in like this, and the 90° angle will be formed something like this, in a way that will start making this arc almost exactly the same as the other one. Therefore, as the distance to the Sun increases, these arcs become more equal. This is so ingenious, no? Although Aristarchus's result was not particularly accurate, it was good enough to realize that the Sun must be much farther away from the Earth than the Moon. His value was 19 times farther, thus the Sun must be 19 times larger, since the angular extent was the same as the Moon in the sky. With the Sun much further away from the Earth than the Moon, the angle of the Earth's shadow is about the same as the angular size of the Sun and the Moon in the sky.

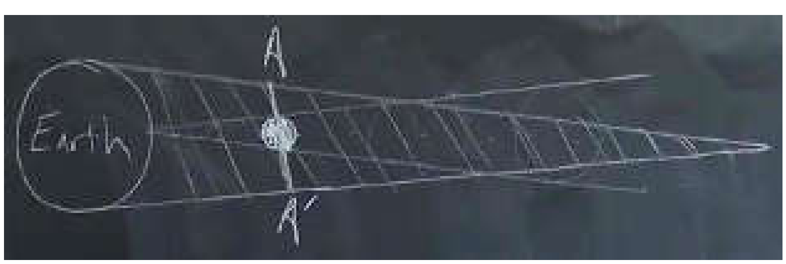
Let us look at that part carefully.



We have the Sun and we have the Earth. Consider the following situation. We are on the surface of the Earth, and we measure the angular size of the Sun. Now we look and see the angular size of the Earth's shadow. Here is the shadow that must be cast behind the Earth due to the fact that the Earth has more or less eclipsed the Sun, for any object that is in this region over here. This θ_2 is the angular size of the Earth's shadow. You can see that, if the Sun is very far away, the angular size of the Sun, which is θ_1, is almost the same as θ_2, the angular size of the Earth's shadow. Notice that these objects are not drawn to scale since the angles depicted are, for clarity of understanding, much greater than the ½° that the objects actually appear as in the sky.

As the final step, let us look at the Earth's shadow in detail during a lunar eclipse. Here we have the Earth and the Earth's shadow. The Sun is a long way away. The Moon in the sky must be within the Earth's shadow.

How is that going to look? We know that the angle that the Moon has in the sky is basically the same as the angle that the shadow makes, so it'll look something like this, and the Moon can be anywhere in this region of the sky.



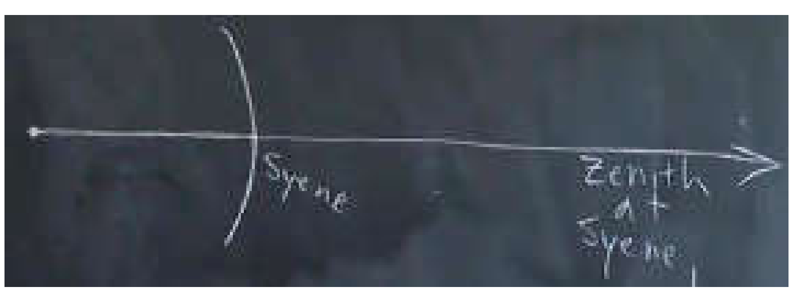
Where do we put the Moon? Here is where the observation of the Moon during a lunar eclipse comes in, because we observe that the time it takes for the Moon to traverse the Earth's shadow is about $^{8}/_{3}$ of the time it takes for the Moon to move its own diameter in the sky. Therefore, the Moon's size must be about $^{3}/_{8}$ the size of the shadow. The only place we can put the Moon in here to meet the requirements of the data, the requirements of the observation, is such that the Moon's size is $^{3}/_{8}$ of the size of the entire diameter of the Earth's shadow, which we can delineate as the line A - A′. We know these angles, they are about ½°. We can put the Moon anywhere in this cone, and still have it have the right angular size, but only when we put the Moon in the proper proportion of the Earth's shadow in size.

4.1 The Size Of The Earth

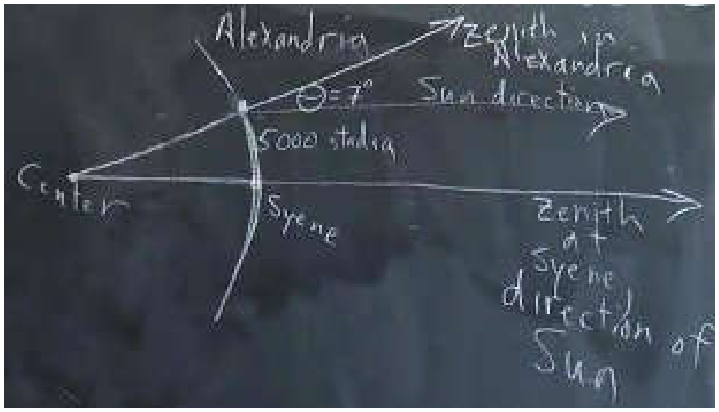
Now we have the relative sizes of the Sun, the Earth, and the Moon, but in terms of the Earth's diameter, we still do not know how big the Earth is. This problem was solved, also ingeniously, by **Eratosthenes** about 50 years later, around 200 BC. To understand how he did this, we have to realize that the Sun is so far away, that essentially all the rays that arrive at the Earth are parallel.

Let us imagine a light source near the Earth. If the Earth is here, and you put a light source over here, the rays from that light source will diverge like this to the top and bottom of the Earth. If you put the object a little further away, the rays do not diverge quite as much. If you put the object much further away the rays diverge even less. If you put the objects, such as the Sun, so far away that you cannot even really tell the difference between these rays, all of the rays that will come in to the Earth are going to be essentially parallel.

Eratosthenes noted that at Syene (Egypt), which is now the modern city of Aswan, on the first day of summer light at noon from the Sun struck the bottom of a vertical well. That meant that Syene was on a direct line from the center of the Earth to the Sun. The picture looks like this.



Here are the surface and the center of the Earth. At this point, if this is the position of Syene on the Earth, the line represents not only the zenith direction at Syene, but also the position of the Sun in Syene.



At the corresponding time and date in Alexandria, which was 5,000 stadia north of Syene, the Sun was slightly south of the zenith. Its rays made an angle of about 7° to the vertical. Here is the vertical in Alexandria pointing this way. Therefore, this is the zenith in Alexandria, and that makes an angle of 7° to the Sun. Here is an angle θ, that because we have gone along the surface of the Earth. The distance of Alexandria from Syene is 5,000 stadia, and at that position, the angle that the Sun makes with the zenith direction in Alexandria is about 7°. Since the Sun's rays are essentially parallel, the angle of 7° between the solar direction and the zenith is the same as if this 7° was subtended from the center of the Earth. Now you see, ingeniously, that these 5,000 stadia can be extended to measure the circumference of the Earth, because we know θ that is subtended by the circle right over here. You can see that θ is to 360° as the distance to Alexandria from Syene, is to the circumference of the Earth. Thus, the circumference of the Earth must be about 50 * 5,000 stadia, or about 250,000 stadia. 250,000 stadia must be the circumference of the Earth.

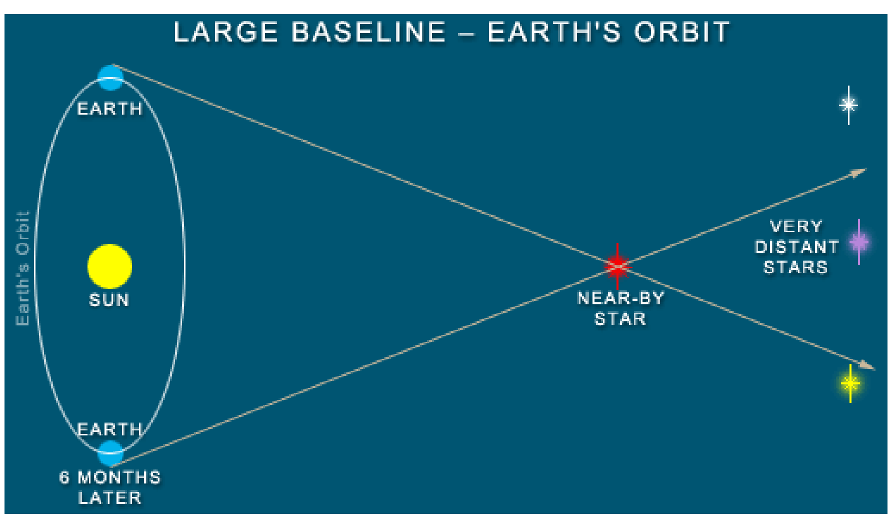
However, what was a stadium? Was it a Fenway Park stadium? Was it a Yankees stadium or what?

There is actually much debate about this, but there is no doubt that Eratosthenes got very close, ranging from 80 – 99 % of the true value for the Earth's circumference. Therefore, now we have a crude estimate of the distance to our nearest star, the Sun. A significantly better estimate was not forthcoming until the invention of the telescope almost 2,000 years later.

The various ingenious experiments designed to measure this elusive number are fascinating to study, and more than just of academic interest. For our knowledge of the distances to the remote stars, which are so far away that we cannot even measure directly their angular diameters, depend crucially on our ability to perform measurements in our own backyard, namely to determine the distance to the closest star, our Sun.

On the surface, it would appear that the situation seems hopeless for even greater distances. I mean it is almost a miracle that we can determine the solar distance. How can we possibly extend our reach to the stars? Well, let us do a little experiment.

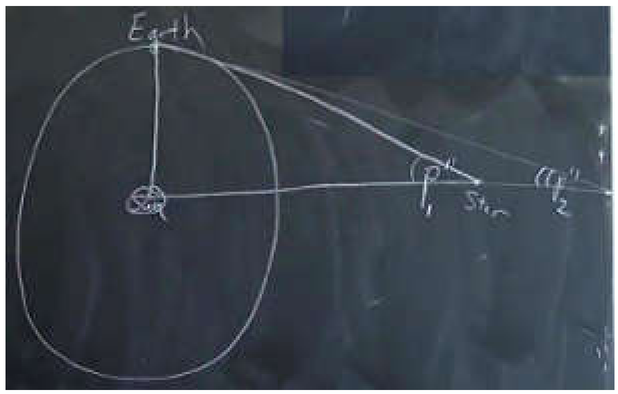
Hold your finger up in front of your eyes and blink your eyes alternately. Notice that your finger moves relative to the objects in the background. This simple example of parallax can now be extended to the orbit of the Earth.



This represents the orbit of the Earth. Therefore, the Earth in June might appear over there relative to the Sun, and the Earth in December might appear there in its orbit. A nearby star will definitely appear to be in a different direction relative to the background that might exist, populated by other more distant objects. The nearest stars then should move relative to the backdrop of the further stars, but the distances involved are so great, relative to the diameter of the Earth's orbit, that changes over the 6-month span, as the Earth traverses opposite sides of its path, are positively miniscule. Indeed, they are so small that many of the ancient Greeks used the lack of measurable parallax to conclude that the Earth was really at the center of the Solar System. Aristarchus, himself, was forced to admit that if the Earth really did orbit the Sun, the distances to the Stars must be vast, indeed.

It was not until 1838 that the first stellar parallax was successfully measured. The displacement was less than $^{2}/_{3}$ of an arcsec. To give you some idea of how small that angle is, let us imagine a golf ball. If you place this ball about 6 mi, or 10 km, away from you, it would subtend an angle in the sky of 1 arcsec. No wonder it was so difficult to measure this.

Note that the smaller the parallax, the greater the distance. Indeed, we can define a new unit of distance in terms of this. Let us look at this.

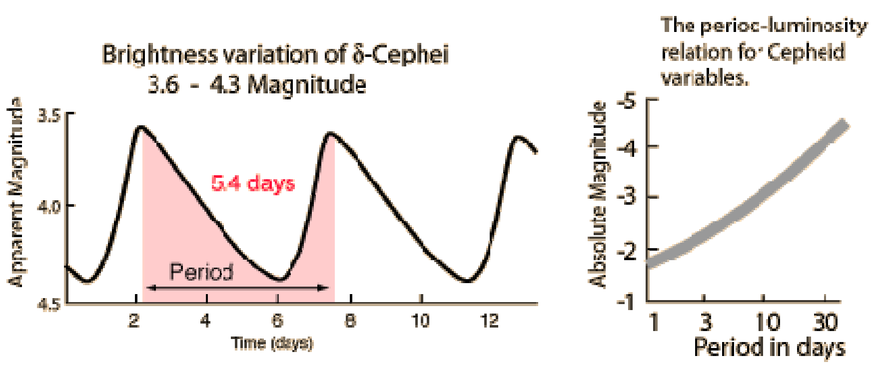


Here is our star and here is the radius of the Earth's orbit. We define the parallax in terms of the radius of the Earth's orbit instead of the diameter, but the idea is basically the same. Notice that if the star gets further away, P_2 is definitely smaller than P_1. The smaller the parallax, the greater the distance. Indeed, we can define a new unit of distance.

$$d = \frac{1}{P}$$

If *P* is measured in arcs, *d* defines a unit of distance called the parsec [pc]. If *P* is 1 arcsec, the distance is 1 pc. Unfortunately, only the nearest few hundred stars have measurable parallaxes, at least from the ground.

Can we ever hope to get measurements of more distant objects? Amazingly, fortuitously, there are classes of very bright stars called **Cepheid variables** that pulsate with different periods depending on their intrinsic brightness or luminosity. What a stroke of good fortune. This means that just by measuring how long it takes for the brightness of these Stars to change, we get for free a measurement of their intrinsic luminosity.



What we see here shows the light curve of δ-Cephei and the period-luminosity relationship for many similar stars. The fact that they are so bright, with some being over 10,000 times the luminosity of the sun, means that they are visible out to very, very far distances, about 30 Mpc or 30,000,000 pc.

However, wait a second, I hear you cry.

Do you not need, at least initially, an independent measurement of the distances to these objects, in order to figure out what their luminosity is in the first place?

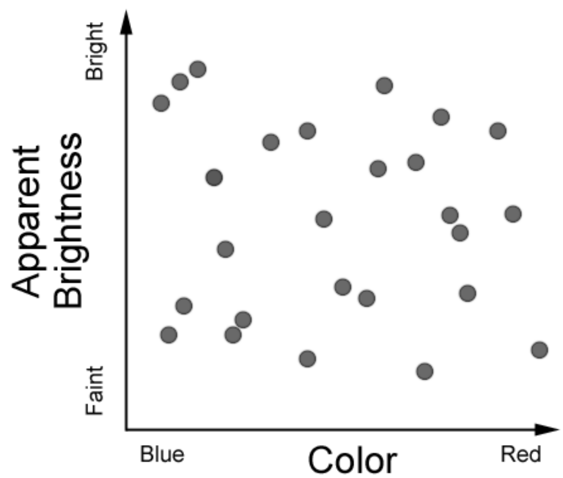
Moreover, right you are. Therefore, the story, while fascinating, is not that simple, but we will touch upon this matter in the coming lectures. Which not only will allow us to use ordinary stars to determine distances, but also provide us with fundamental data concerning the nature of stellar evolution, and the role that this plays in our understanding of the incredibly hot X-ray sources in our Galaxies and beyond.

Stellar Evolution And White Dwarfs

1 Putting It All Together - The HR-Diagram

In the early decades of the 20th century two momentous discoveries were made that would change the face of astronomy forever. The first was Henrietta Leavitt's discovery of the Cepheid variable stars period-luminosity relationship. As we have seen, this gave astronomers at long last a means to probe the distances to many more objects than were accessible via parallax measurements, and hence now we could determine the intrinsic luminosity for a sizable number of Stars. In addition, another woman, Cecilia Payne, discovered that the spectral types of stars that were classified using atomic spectra were actually representative of a temperature sequence of the surface layers of stars.

However, even before this latter understanding Ejnar Hertzsprung, working in Denmark, and Henry Norris Russell, working at Princeton, began graphing the correlation between spectral types of stars and their intrinsic luminosity. The results were breathtaking and led to far-reaching understanding of not only the characteristics of stars as they appear today, but also the nature of stellar evolution. How the stars change over vast periods of time. Let us see how this came about.



First, notice what happens if you just take a bunch of stars, and do a scatter plot of their apparent magnitudes and colors, or spectral types. You will get a random useless mess, such as shown here.

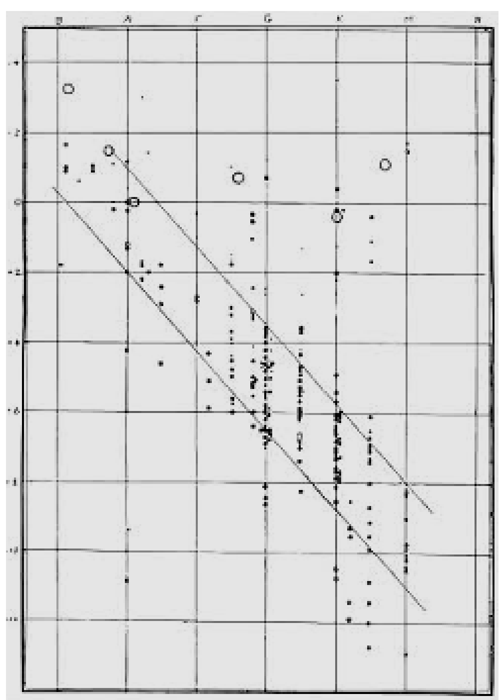


Illustration 35 : Henry Norris Russell's first plot

The reason for this is that the stars can be at any apparent magnitude, because their distances are all different. Now we can see what happens when we know the stars distance and hence intrinsic luminosity. Here you see Henry Norris Russell's first plot using about 200 stars with known absolute magnitudes. Its crude, but you can see the pattern emerging.

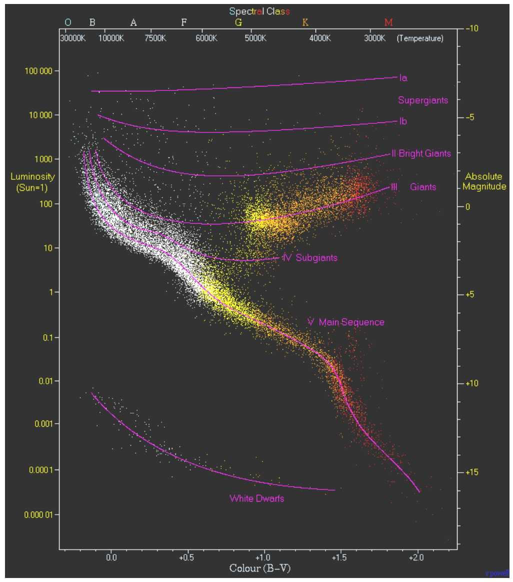


Illustration 36 : First plot you can call HR-diagram

Here is a refined version incorporating the ideas spawned by Henrietta Leavitt, Cecilia Payne, and Ejnar Hertzsprung as well. We see 23,000 stars whose spectral classifications and luminosities are known.

The first thing that immediately strikes you is that the stars are not randomly distributed. There is a line running diagonally across the graph that contains the vast majority of all the stars. It is called the main sequence. This non-random pattern is a very powerful indicator for astronomy. It means that when you observe, say a cluster of stars, whose members are more or less at the same distance from the earth, you can look at their HR-Diagram, fit their main sequence to this calibrated one, and thereby immediately find out how far the cluster is from the earth. All you need to do is compare the cluster members observed magnitudes, and compare them to the absolute or intrinsic magnitudes shown here. Voila, you have their distance via the inverse square law. However, before we explore this further let us look at how many ways we have to express both the spectral type of the stars and their associated luminosity.

First, you can see that the spectral classification scheme we talked about further is associated with the stars temperature. This was Cecilia Payne's work. Also at the bottom is another often-used indicator called the stars B-V color. This number refers to the measurement of the brightness of the star through two color filters. In this case, the B-filter, which emphasizes the blue portion of the stars light, and the V-filter, which emphasizes the visual or more yellow part of the output. It turns out that comparing these two measurements, by subtracting the V-magnitude from the B-magnitude, gives a quick and reliable way to compute the spectral type and hence temperature as well.

Now, let us look at the Y-axis. At the left, we see the value of the luminosity is compared with that of the sun. Corresponding to that at the right is the value of the stars absolute magnitude, which is defined as the magnitude that the star would have at a distance of 10 parsecs.

A moment's thought will show you that in order to know that number, the absolute magnitude, you must know the star's distance, so you can convert the observed apparent magnitude to the value it would have at 10 pc.

Now look what you can do. You can stand the problem on its head. Imagine you observed the spectrum of a star that looks identical to, say, one whose B-V color is 1.5, and whose luminosity is 0.01 times that of the sun. You know then that your star has an absolute magnitude of +10. Now, by comparing your observed apparent magnitude to the value of +10, you immediately know the distance. You have derived what is called a spectroscopic parallax. It is not really a parallax at all, but a way to get the distance to stars for which the parallax might be immeasurable, because it is too far away.

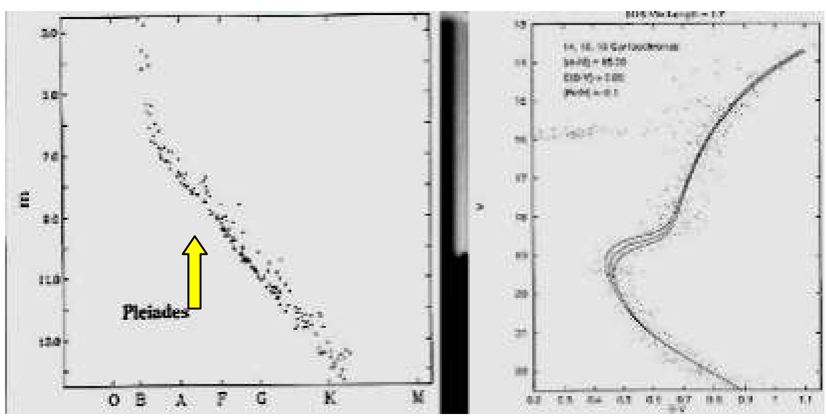
Therefore, you can see how powerful the HR-Diagram can be. Now we can go beyond this and using some theoretical results of stellar structure understand how stars evolve in time. This, in turn, will lead us to a basic understanding of how some of our X-ray sources come into being.

The first thing that guides us is the rather surprising fact that stars have a fairly restricted range of masses, again the name of Henry Norris Russell pops up. It turns out that by the middle of the 20th century we had a fairly accurate appraisal that the very low luminosity stars had masses of about $^{1}/_{10}$ of a solar mass, while the upper end of the scale was populated with stars of about 50 solar masses. That range, a factor of about 500, stands in stark contrast to the range in luminosity, which you can see is a factor of 10 billion.

How is that possible?

Clearly, one-way out is if the high mass stars exhaust their fuel much more rapidly than the low mass objects. In other words, they burn a tremendous amount of fuel, hence providing a high luminosity, but they must burn out very rapidly since they are not billions of times more massive than there low luminosity counter parts. And indeed, our model show that stars at the very low end of the main sequence have enough fuel to last for over 10,000,000,000 years, whereas at the high end objects exhaust their supply in a mere 1,000,000 years or so. Therefore, we ought to be able to use observations of various clusters of stars to see this effect, if indeed some are older than others.

Here are two clusters, one an open cluster called the Pleiades, and the other, a globular cluster called M15. These are truly beautiful sights in a telescope. Now, let us look at their HR-Diagrams. These diagrams for clusters are sometimes called cluster magnitude diagrams as well.



You can see that the main sequence of M15 is much shorter. In fact, the arrow that you see in the plot of the Pleiades stars marks the so-called turnoff point of the main sequence that you see for M15. Evidently, M15 is much older than the Pleiades, since all the high-mass, high-luminosity stars are simply not there, at least not on the main sequence. There are other clues that point in this direction as well. Therefore, now let us combine many clusters into one diagram. What you get is shown here.

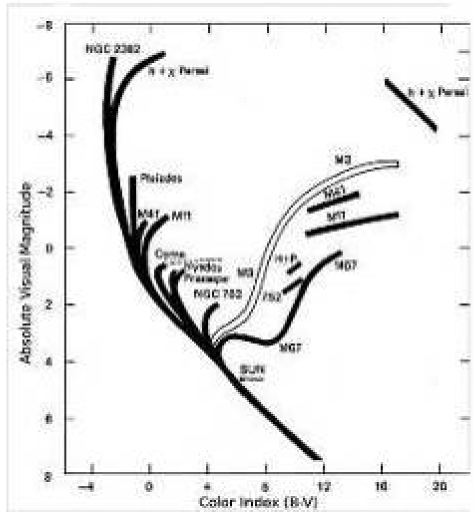


Illustration 37 : Cluster HR-Diagram

You can clearly see the trend off the main sequence as you go further down towards the low mass positions. If our ideas about this are correct, we should be able to model these various clusters, and see how they evolved with time. Indeed, we can do this quite well.

However, where do all those evolved stars go?

Their paths are torturous and complicated, but it appears that when stars like the sun exhaust their fuel, they end up in the stellar graveyard indicated by the white dwarf area of our diagram. These objects, for the most part incredibly hot, are astonishingly small, and turn out to be about the size of the Earth. How do we know this? Well, we remember our old friend:

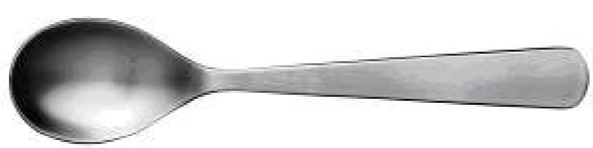
$$L = 4\pi r^2 \sigma T^4$$

Equation 4 : Stefan Boltzmann law

T is very high, but we know the luminosity is very low. The only way that this can come about is if the size is extremely small. Let us see how unusual these objects really are. Imagine a typical white dwarf then. The size, its radius, is about equal to the size of the Earth, $6*10^8$ cm, and the mass is about that of the Sun, $2*10^{33}$ g. Let us compute its average density. The average density is given by the mass divided by the volume. For this object, it turns out to be:

$$\begin{aligned} \overline{\rho} &= \frac{M}{V} \\ &= \frac{2*10^{33}}{\frac{4}{3}*\pi*\left(6*10^8\right)^3}\left[\frac{g}{cm^3}\right] \\ &\approx \underline{2*10^6 \frac{g}{cm^3}} \end{aligned}$$

Now this is just a number. Okay, let us see if we can put this in real perspective.



Here we have a teaspoon. It has a volume in the spoon part of about 5 cm^3. Let us scoop up one teaspoon of material from a typical white dwarf.

How much will that material weigh? Alternatively, what will its mass be?

Well, we know that. It is just going to be bout 10,000 kg. This mass is about the same as a typical 53-foot semi tractor-trailer, and it turns out that these astonishing objects play a prominent role in the X-ray universe.

2 Of GK-Per and White Dwarfs

Now we begin our exciting in depth source-by-source analysis of some of the most interesting objects in the sky. X-ray astronomy has been a curious mix of finding unusual behavior in previously known objects, plus the startling discovery of hither to completely unknown sources. The latter objects in the early days meaning the 1960s were designated by the constellation in which they resided appended with X1, X2, X3, etc., in order of their discovery. Thus, we had a mixture of names such as AM-Her, where *Her* is short for the constellation Hercules, and Sco-X1 or Cen-X3, where *Sco* stands for Scorpio and *Cen* indicates Centaurus.

2.1 Nova Persei 1901

We will begin our source-by-source saga with the well-known object GK-Per, a double star in the constellation of Perseus, which has a white dwarf as a member of the pair. The nomenclature is pretty arcane, but any star with one or two capital letters at the beginning of its designation means that the star is variable in light. Indeed, late in the evening of February 21, 1901, a Scottish clergyman, Thomas Anderson, was working home in Edinborough where he saw a brilliant star in Perseus where none was present before. The next day, he notified the Greenwich Observatory, and found out that he was the discoverer of Nova Persei 1901, the first new star of the 20th century.

Back at the Harvard College Observatory, it was found that this star had been seen before on photographic plates, but at a magnitude 13, about 500 times fainter than the faintest star visible to the naked eye. A number of photographs revealed that the star had small fluctuations in light, but never anything like the factor of 10,000 that Anderson's observation implied. Indeed, at maximum light, two days later, Nova Persei was briefly emitting about 400,000 times more light than it had done previously. Fortuitously, one of the Harvard photographs was taken just two days before the outburst. Thus, in less than four days the star increased its luminosity by 400,000. That is what I call some explosion.

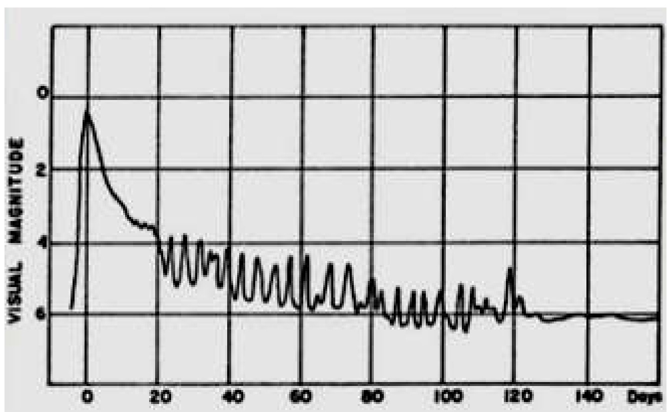


Illustration 38 : Nova Persei 1901 - Light curve

In the light curve displayed here, you can see those six days after its maximum the Nova had faded by about a factor of six. It continued to fade smoothly until after about two weeks, when a series of oscillations set in with a period of about 4 days. These fluctuations lasted for several months, while the star faded some more until at last 11 years after its outburst it was back to its original brightness, apparently oblivious of its former glory. However, decades after its spectacular outburst, Nova Persei 1901, also designated GK-Per, began in 1966 to display smaller outbursts of about three magnitudes, an amplitude occurring about every 3 years.

Illustration 39 : Nova Persei 1901 - Light curve 1965 – 1970 (1-day means)

You can see them in this long-term light curve shown here. It was during one of these outbursts in 2002 that NASA's CHANDRA satellite looked at the object to see if any X-rays were being emitted. Let us go to DS9 and check it out.

At this point, please watch "Analyzing the Universe003.mp4"

Video 3 : GK-Per (DS9 analysis)

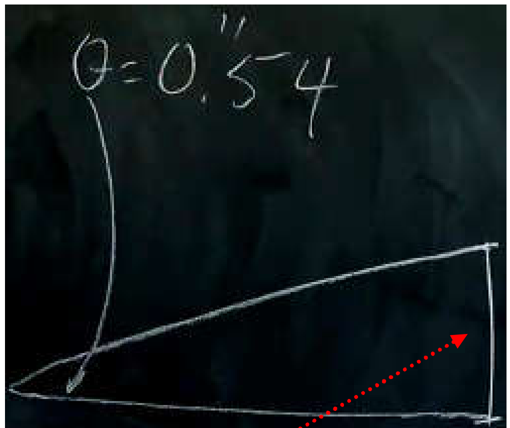
The idea is this - in one year the distance the shell expands is:

$$D = vT \quad \text{Distance = Velocity* Time, or:}$$

$$1{,}200\ {}^{km}\!/\!_{s} * 3 * 10^{7}\,s$$

$$= \underline{3.6 * 10^{10}\,km}$$

$3 * 10^7$ is the approximate number of seconds in one year.



This distance, which we can represent just by this little line, is corresponding to an angle θ = 0.54”; therefore, we know the distance, we know the angle, and we can calculate through simple trigonometry what the distance is. It turns out to be about 470 pc, or about 1,500 ly.

Pretty neat, huh?

At this point, please watch “Analyzing the Universe004.mp4”

Video 4 : Fourier transform (power curve) of GK-Per

Therefore, we have an incredibly accurate clock in the sky, stable to a spectacularly high precision over about 20 years at least. What could provide such a mechanism?

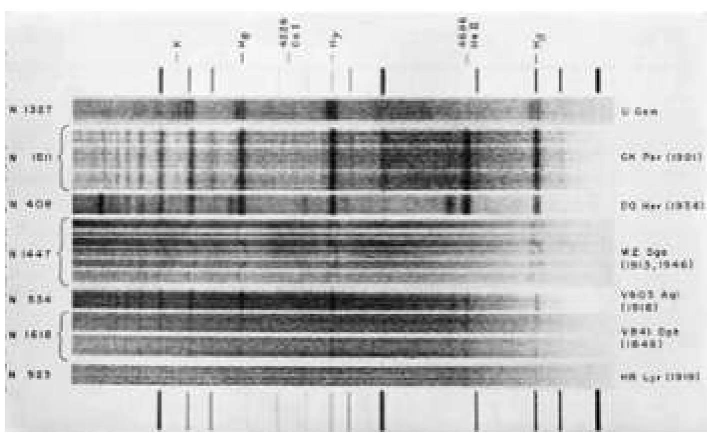


Illustration 40 : Sample of spectra of old nova

Again, some clues are given to us by the optical spectrum of this object shown here. Looking at this visible light we see something quite strange, all the spectral lines that are there we expect to see coming form a very cool star, even cooler than our Sun, except for one line at 4,686 Å. It is the strongest line in the spectrum, and is the fingerprint of He^{-2}, or ionized Helium. This is incredible!

Why?

Because in order to ionize He you need an environment that is unbelievably hot; at least ten times hotter than the sun. Therefore, here we have an example of a composite spectrum, one that can only be explained by the existence of a double star. One very cool, and one very, very hot.

As we saw earlier, when we studied the HR-diagram, hot stars come in basically two flavors; one group astonishingly bright, much more massive than the Sun, and the other the stellar graveyard of objects very much like our Sun cooling down like a dying ember and being very small.

How do we know they are small? Remember that the luminosity of any star can be given by:

$$L_* = 4\pi r^2 \sigma T^4$$

Equation 5 : Total energy output of any blackbody radiator

We know that the luminosity is very small for these objects, and the temperature is very high. The only way we can have a small luminosity is if the size of the star, its radius, is very small indeed. In fact, the radii of most white dwarfs are about equal to that of the Earth. Imagine that: A mass about equal to the Sun in a size no bigger than a fairly small planet like the Earth.

Back to GK Per. We have an object with a star similar to the Sun, a bit cooler being a K-star, and a hot white component. We know it cannot be very luminous in the visible part of the spectrum, because we know its distance. At that distance, a hot O or B-star would make GK Per hundreds of thousands of times brighter than we observe it. Therefore, the second component must be a white dwarf. Is there any other clue that this is the correct picture?

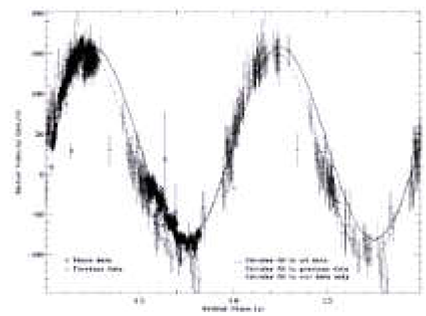


Illustration 41 : Doppler measurement of GK Per

Yes! Again, using Doppler measurements, we can see the composite spectral lines moving back and forth over a period of about 2 days. You can see that in the data shown here. This cosmic dance, as we shall see, is indicative of a double star system whose components orbit each other with a period of about 2 days.

What about our 352 s period, what can that be, and which star is responsible?

It cannot be an orbital period, because that has already been spoken for in the two-day clock observed in the spectral lines. Now let us look at the next obvious choice; rotation of one of the stars. Let us start with the K-star.

We know from theoretical considerations that these are objects about 0.7 times the radius of our own Sun. This will make this star a ball equal to a radius of about $5 * 10^8$ m. We can also use the binary periodicity observations to show that the mass of the K-star is about ½ of a solar mass, or about $1 * 10^{13}$ kg. Now if this star is spinning around in 352 s, this means that the speed at the equator must be:

$$\upsilon = \frac{2\pi r}{T}$$

This means its speed is about $9 * 10^6$ $^{m}/_{s}$. Boy that is fast!

What can possibly prevent the stuff from flying apart at the equator?

We would need some sort of force to hold it together.

Is gravity up to the task?

Let us see.

You might remember that objects moving in a circle of radius *r* are accelerated to the centre of that circle through their centripetal acceleration.

$$a = \frac{\upsilon^2}{r}$$

If you have not seen this before, do not worry, we will demonstrate it shortly, but right now let us just use this fact to see what we can find out. If we are on the surface of a K-star, spinning around every 352 s, we need an acceleration of $\frac{\upsilon^2}{r}$. If you put in the values that we just found, you find that the acceleration of that material on the equator of the star ought to be about $1.6 * 10^5 \, {}^{m}\!/_{s}\!/_{s}$.

Is gravity up to this task? We know from Newton's Law, which we will also discuss later, that a test object of mass *m*, in the vicinity of an object of *M* will feel a force:

$$F = ma$$
$$= \frac{GMm}{r^2}$$

Thus the acceleration that gravity can provide towards the center of the K-star is:

$$a_{Grav} = \frac{GM}{r^2}$$

You have something sitting on the equator of the star; it is a distance *r* from the center of the star. The mass of the big star is *M* and the acceleration that gravity will provide will be equal to this quantity. Now *G*, the gravitational interaction constant, is in these units, $6.7 * 10^{-11}$. You can look these numbers up; I mean there really is good reason to have something like Wikipedia handy so you can check on this. We know what the mass is, and we know what the size of the object is. If you work this out, rather than doing it on the blackboard, it would be a very good exercise for you to do this yourself, you find that this amount of acceleration due to gravity on the surface of a K-star is about $2.7 * 10^2 \, {}^{m}\!/_{s^2}$.

Now, if you compare these two numbers, the number that is provided or can be provided for by gravity to the number that we actually would have for a mass sitting on the surface of a spinning K-star, you can see that gravity simply can't do the trick. The acceleration, provided by gravity, is grossly inadequate to prevent the star from flying apart at the equator. It needs much more of a pull than gravity on the surface of a K-star can provide.

What about the white dwarf? Again, from spectral observations we find that the mass of this component is about equal to the mass of the Sun, which is $2 * 10^{30}$ kg. The radius of this object is about equal to the radius of the Earth, so the radius of our white dwarf is about $6 * 10^6$ m. Now we can go through the same calculation as we did before. We could calculate the speed at the surface of the white dwarf; calculate the acceleration where now you use the white dwarf speed and the radius of the white dwarf. If you do that, you will find that the acceleration at the surface of a white dwarf is equal to about $1.6 * 10^3 \, {}^{m}\!/_{s}\!/_{s}$.

Is gravity up to this task?

Again, we calculate this. We find that gravity can provide an acceleration of about $4 * 10^6 \, {}^{m}\!/_{s^2}$. Yes! Gravity can do the trick. $4 * 10^6 \, {}^{m}\!/_{s^2}$ is much more than what we need to prevent something on the surface of a white dwarf from flying off into space. Therefore, gravity can provide more than enough pull to keep the star intact, and still have it spin around every 352 s.

It appears we have solved the mystery, but what is it that is changing every 352 s that allows us to see the star varying at all?

I mean, just because an object is rotating does not mean that we are going to be able to see it. There must be something that is tied to the rotation period as the star spins around on its axis, and in order to see what that might be we will examine our next X-ray source, Cen X-3.

Orbits, Gravity, And Clocks In The Sky

1 Orbits

Today I want to talk to you about a big problem that astronomy has. That is determining the mass of astronomical objects. You see, astronomy has a big disadvantage when it comes to analysis in general.

Why?

Because we cannot change things! Unlike a terrestrial physics or chemistry lab, where we can vary many conditions that might affect a given experiment, such as voltage, or pH, or a magnetic field, in astronomy we have to accept the experiments that nature gives us. Thus, fundamental quantities that we take for granted on the Earth, such as the mass of an object and its distance away from us, become exciting challenges for us in the celestial realm.

Why is the determination of mass so challenging?

Primarily it is because gravity is such a weak force, and the only means by which astronomically sized objects can be measured. Let us examine this in detail. To do this we travel back in time and visit Europe in the 17^{th} century. As we shall soon see, time itself was part of the problem. Galileo, and then Newton, were hard at work. The 'Holy Grail' of the nature of forces in motion was being sought.

However, what is a force? In addition, on what does it depend?

Aristotle chimed in first, noting that if a force, or impetus as it was called, was stopped, and the object to which the force was applied also stopped. Therefore, it was obvious; the natural state of an object was at rest. Thus, force is proportional to velocity:

$$F \propto v$$

Force must be proportional to the velocity, since even to maintain a constant speed, you seemed to need a force. Therefore, an error propagated down through the centuries, until the great Galileo in a brilliant series of experiments involving incline planes put forward the positively absurd notion that an object could move forever at a constant velocity with no force applied at all. Uniform, perpetual motion was indeed possible. In the absence of a force, the velocity of an object would not go to zero, but stay constant.

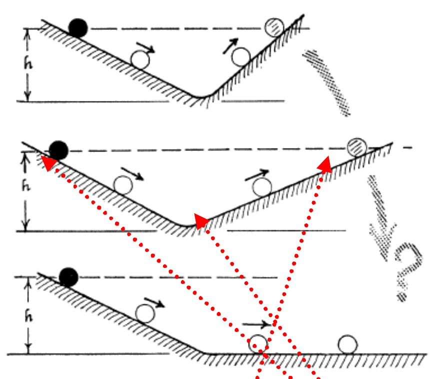


Illustration 42 : Galileo's experiment

How did he show this?

Galileo noticed the following. If you have a ball on an inclined plane and the ball rolls down the plane, it always goes back to the same height when it rolls back up the plane, always to the same height as it started. Now, look and see what he did. If the ball rolls down the plane, and now the plane has a slightly different angle, it will roll further along the plane, back to the same height as it was initially, and you can see where he is going with this now. The ball rolls down the plane. Now, the plane goes up like this, here is the height the ball rolls down, the ball rolls over, all the way over to here, and now, for the 'piece de resistance,' he rolls the ball down the plane. Now instead of having any angle at all that has an upward swing, you can now imagine that if you get that ball rolling all along a plane that is exactly horizontal it will never ever stop.

Even Galileo commented that this seems hard to believe, yet this is what his experiments showed. It is one of the first to usher in the scientific age; he believed that the universe must be examined in the light of data, and not understood according to pronunciations by authorities, be they philosopher like Aristotle or theologians like pope Paul V. Therefore, this simple idea experimentally determined, that motion could be maintained in the absence of a force finally led Newton to the understanding that force was proportional to acceleration. Force is proportional to acceleration, and mass, as the resistance to motion, completes the idea of inertia.

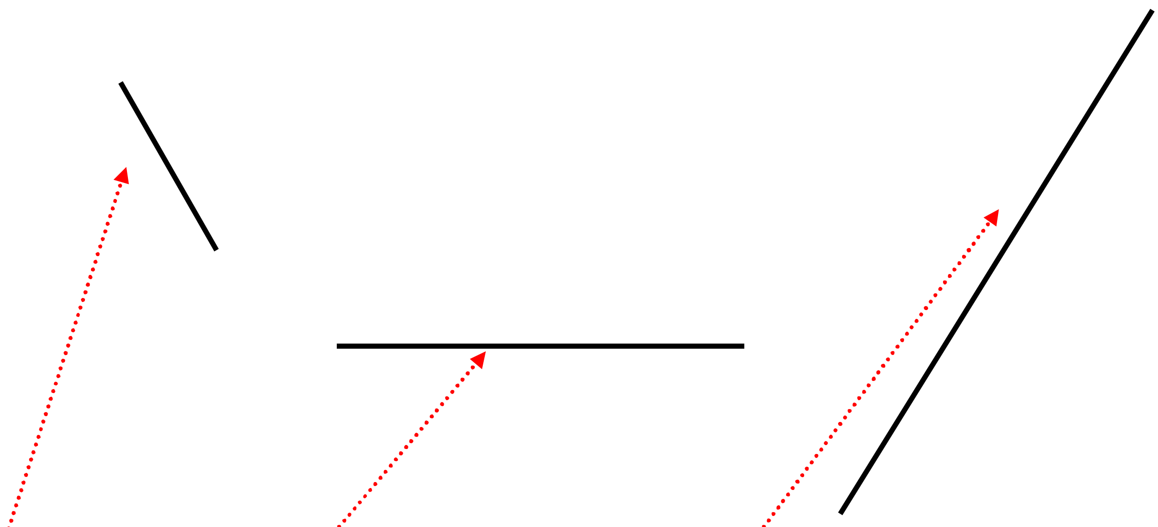
$$\vec{F} \propto \vec{a}$$
$$\vec{F} = m\vec{a}$$

However, what is about all those little arrows? What do they mean, and why are they important?

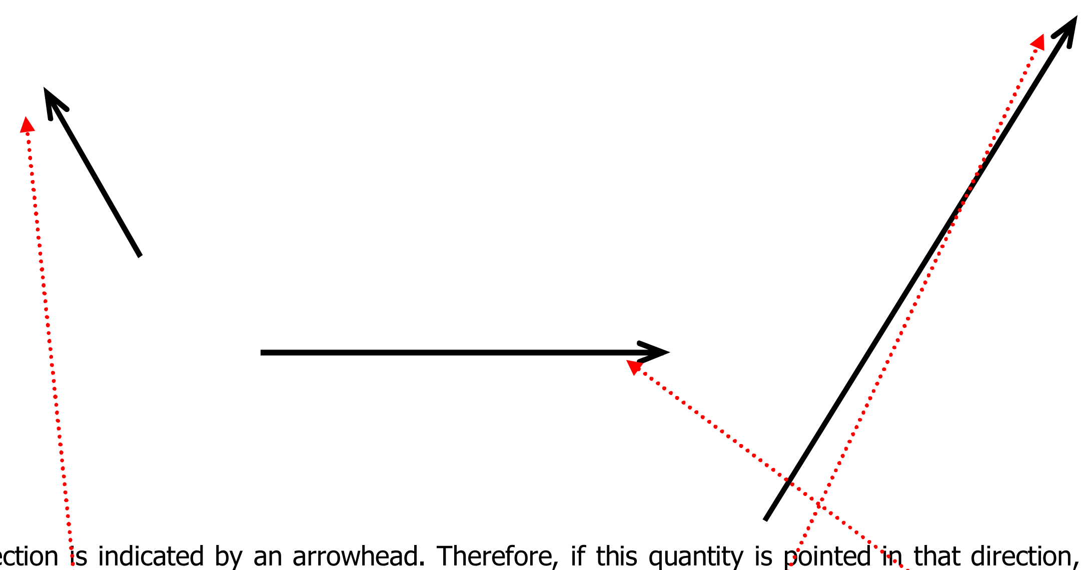
To understand this we need to take a little side street down the road marked vectors.

1.1 Vectors

What is a vector? It is nothing more than a mathematical quantity, a number, which has a direction associated with it. The quantity is indicated by a length.

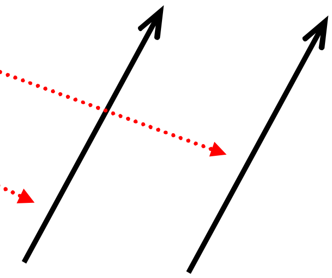


This being a small quantity, this being a medium sized one, and this being a fairly substantial length.

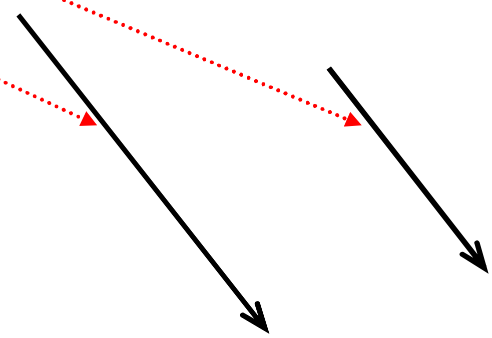


The direction is indicated by an arrowhead. Therefore, if this quantity is pointed in that direction, we draw an arrowhead there. If this quantity is drawn in this direction, we have an arrowhead there, and if this quantity has a direction associated in this fashion, we draw the arrowhead over in that position.

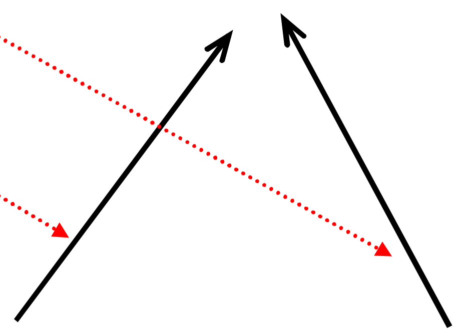
Thus, two vectors, **A** and **B**, are identical as long as their lengths and their directions are the same. Therefore, if this is $\vec{A}$, this can be $\vec{B}$, looks pretty good. You might have to use a little bit of imagination there.



However, the fact that they are written in a different part of the blackboard is irrelevant. Choose some other combinations. $\vec{C}$ is not equal to $\vec{D}$, even though their directions are the same, because the length of $\vec{D}$ is not equal to the length of $\vec{C}$.

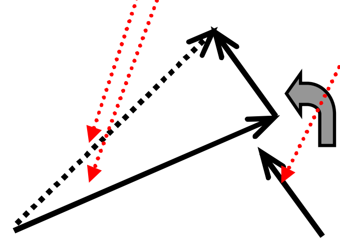


$\vec{E}$ is not the same as $\vec{F}$, even though their lengths are the same. The magnitude of $\vec{E}$ and the magnitude of $\vec{F}$ might be equal, but the directions are not the same.



1.2 Define Vector Addition

Taking the tail of one vector and placing it on the head of another, drawing the resultant from the beginning of the first one to the end of the second one. If this is our $\vec{A}$, and this is our $\vec{B}$, what we do is, we take $\vec{B}$ and put it in exactly the same direction as it has and preserving its length. Put it on the head of $\vec{A}$, and then we draw the resultant from the beginning of $\vec{A}$ to the end of $\vec{B}$. This becomes $\vec{A} + \vec{B}$.



Okay, tail to head, tail to head, tail to head. This is our vector. Now, we can call that vector $\vec{C}$, instead of calling it $\vec{A} + \vec{B}$, let us denote it by another letter $\vec{C}$, and now you see that in a way we have been able to define addition.

1.3 Define Vector Subtraction

Look at what happens here:

$$\vec{C} = \vec{A} + \vec{B}$$

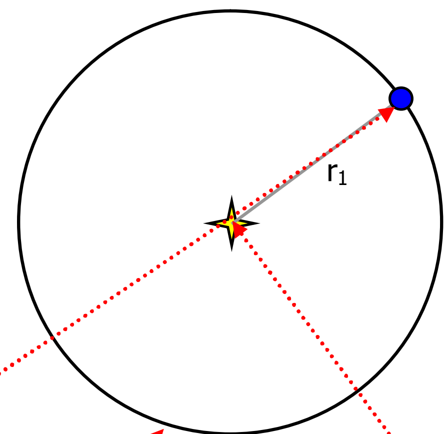
That means that:

$$\vec{B} = \vec{C} - \vec{A}$$

Therefore, what happens in subtraction is you take the two tails, the tail of $\vec{C}$ and the tail of $\vec{A}$, you connect the heads, and that defines your vector $\vec{B}$, which is a subtraction.

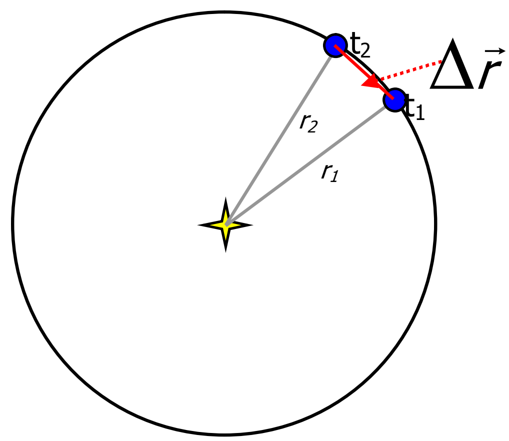
Now where is all this going?

Why do we even bother with this stuff? The reason we bother with it is because experimentally it has been determined that force, believe it or not, depends exactly like a vector. It has all of its characteristics associated with it with vector addition and vector subtraction and other operations that we can also define.



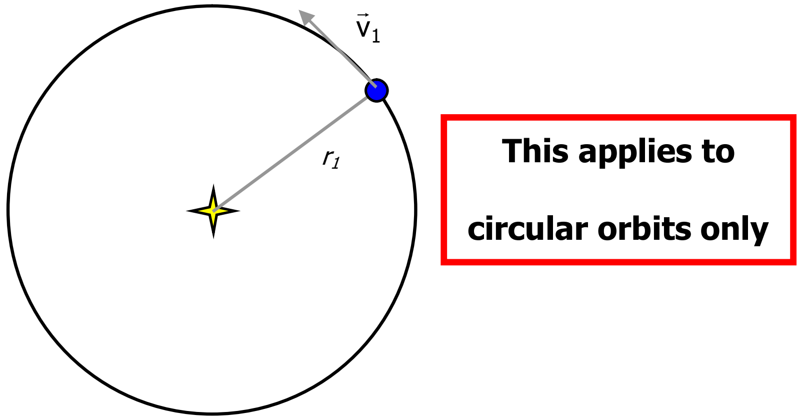
Let us look at a simple example A planet is moving in a circular orbit around a star, or one star is going around another star. The situation is as follows: Here is our circular orbit, here is the center where this big mass is supposedly, and here is a place where our planet is located. The position of the planet can be given by a vector *r*, and we will call it r_1, because it is a moment in time.

A little bit later, the planet has moved its position to a place r_2 at time two. In addition, in fact, it is supposed to be the same size circle, but, you know, now you can see that there has been a change in the position of the planet from t_1 to t_2. We can see what that change is by just drawing these two vectors, r_1 looks reasonable, r_2 looks reasonable. As we did before with subtraction, this becomes our change in r. If you go from r_1 to r_2 you have to add this little amount, which is $\Delta\vec{r}$. The angle between these two positions can be denoted by θ.



Now, what is happening as this planet is moving around?

Not only is it changing its position, the reason that it is changing its position is because it is moving. I think you can convince yourself that the velocity of the planet must be denoted by a vector that is perpendicular to the position.



Why does it have to be perpendicular?

Well, I am not going to answer that question for you. I want you to see on your own if you can convince yourself that it has to be perpendicular, and it cannot be something going in other directions. It must be at a right angle to the position r_1. We can call that vector the velocity vector. Just as we have a velocity at t_1, we also have a velocity at t_2, also perpendicular to r_2. Moreover, if it is in uniform circular motion, the lengths of these two vectors must be the same. If they were not the same, then the motion would **not be in a circle**. Something would be happening, to the position of t_1 versus t_2, so that you would not be able to get from r_1 to r_2 if the speed of the object were actually changing.

Now let us look carefully at our velocity vectors v_1 and v_2. If we draw v_1 and v_2 we are going to have in exactly the same fashion as we had a $\Delta\vec{r}$ in the above situation. We are going to have a $\Delta\vec{v}$.

Guess what that angle is?

That angle is θ.

Why?

Convince yourself that this angle has to be the same as this angle for r. Therefore, what we are faced with are two similar triangles in which we can now look at various sides, and see if we can come up with a relationship for the acceleration.

I want to point out one very important thing. Look at the direction of $\Delta\vec{v}$. $\Delta\vec{v}$ is pointing back in towards the center of the circle. This will be a key point when we look at how this relates to the gravitational force. As v_1 gets closer and closer to v_2, namely a smaller and smaller interval of time of, is observed to elapse, that $\Delta\vec{v}$ gets closer and closer to being pointed exactly towards the center of the circle.

Let us look at these two triangles, what we are after, is an expression for the acceleration.

The acceleration is the change in velocity divided by the change in time.

$$|a| = \frac{\Delta_v}{\Delta_t}$$

Now, velocity already contains a time, right? It is just the time rate of change of position. Therefore, now we can use these triangles, and see if we can come up with an interesting formula for what the so-called centripetal acceleration is. If we look at these triangles, we notice that:

$$\frac{\Delta_v}{v} = \frac{\Delta_r}{r}$$

Where now I am dropping the subscripts here because we are just looking at the magnitude of the acceleration, and now we can work with these particular quantities. You can see that we are going to have to have a Δ_t in here somewhere, so what we are going to do is, just divide both sides of the equation by Δ_t.

$$\frac{\Delta_v}{v * \Delta_t} = \frac{\Delta_r}{r * \Delta_t}$$

Now, look at this. $\frac{\Delta_v}{\Delta_t}$ is nothing more than our acceleration and $\frac{\Delta_r}{\Delta_t}$ is nothing more than the velocity, or the speed, at least the magnitude of the velocity. Therefore, now you can see that:

$$\frac{\Delta_r}{\Delta_t} = v \quad \text{implies} \quad \frac{\Delta_v}{\Delta_t} = v \quad \text{following} \quad \frac{\Delta_v}{\Delta_t} = \frac{v^2}{r}$$

Now we have established that in circular motion:

$$|a| = \frac{v^2}{r}$$

We have also established that by the direction of *v* being in towards the center of the circle it is in the opposite direction of our vector *r*, therefore, that we can write the acceleration in general:

$$a = \frac{-v^2}{r}$$

In other words: the magnitude given by $\frac{v^2}{r}$, and the direction given by the minus sign of *r* in towards the centre of the circle. That is all we really need to know to be able to determine a lot about the dynamics of planets going around stars, stars going around yet more massive stars, or, for instance, the Sun going around the center of the Milky Way. In order to pursue that we will continue with a discussion of the gravitational force.

1.4 A Footnote Regarding Time

I want to tell you why it took so long for us to understand what the nature of forces were. Why did it take till the 17th century before we could figure it out?

The key problem was the quantity associated with Δ_t. Notice that Δ_t appears in both the expression for velocity, and also in the expression for acceleration.

How do we measure Δ_t? Well, we all know how we do it now. We look at our watch, and we say one, two, three, four, or we have a stopwatch were we can push a button and get evermore-accurate divisions of any unit of time that we want. However, in the 17^{th} century it was not until around 1750 that Christiaan Huygens was able to invent an accurate pendulum clock. All of a sudden, we did not need to use the Earth's rotation or sand dripping in an hourglass in order to figure out what the elapsed time was. Therefore, starting in the 1750^s when clocks were invented that gave us enough precision into which we could measure and divide a second. That was when the era began that we were able to actually figure out what the difference was between a result that gave us a velocity or a result that might yield an acceleration.

2 A Matter Of Some Gravity

Last time we obtained a bit of insight into that most famous of all equations in classical mechanics, better known as Newton's second law. That says:

$$F_{net} = m * a$$

Equation 6 : Newton's second law

This particular equation is surprisingly subtle, and we are going to ignore most of those subtleties, but I should at least tell you that:

This is a vector equation. Force has a particular direction, and the acceleration also has a particular direction. In addition, you need to sum all of the forces that might be acting on an object. Therefore, we really have a net force, because forces can pull in different directions, and so this particular equation can yield insight into the way astronomical bodies can move.

We also derived the acceleration, *a*, for circular motion, and we found that the magnitude of that acceleration was given by:

$$|a| = \frac{v^2}{r}$$

R is the distance between where the center of the circle was, and where the object was rotating around. Now we are ready to see what the left-hand side of Newton's law has in store for us by applying it to simple astronomical systems.

Newton found out, after countless generations of scientists and would-be scientists over the centuries tried their luck and skill at figuring out the problem, that the gravitational force between two point-like objects was:

$$F = \frac{GMm}{r^2}$$

We usually just use *M* and *m* to represent the masses of the two objects involved. Again, we are going to assume that this is a vector, and we are not going to worry about putting arrows on everything, because sometimes that can get a little bit cumbersome. This is simple but profound. *G* is a constant that is surprisingly difficult to get accurately, because gravity turns out to be a very weak force, but we do know the value of *G* to about $^1/_{10}$ of 1 %. Let us see what the consequences of our understanding of these ideas are.

First, imagine that *M* is the sun and *m* is any planet. Then we have:

$$F = \frac{GMm}{r^2} = \frac{m\upsilon^2}{r}$$

Where now we are substituting for the acceleration, our understanding for how things move in a circular orbit. If we solve for υ^2, we find that:

$$\upsilon^2 = \frac{GM}{r}$$

Notice that this is independent of our *m*. Therefore, if we look at the speeds of planets in their orbits, and these are pretty close to being circular, we should see that:

$$\upsilon \propto \frac{1}{\sqrt{r}}$$

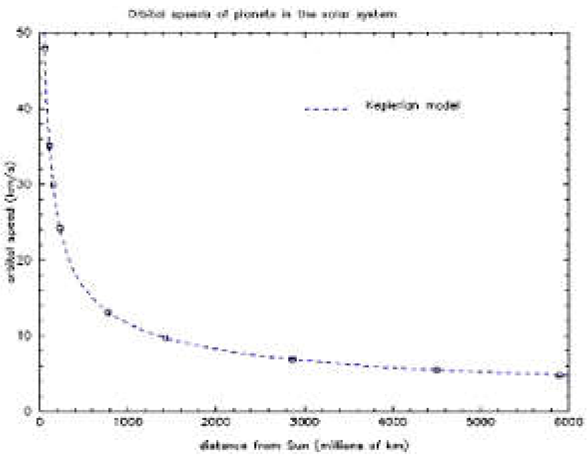


Illustration 43 : Orbital speeds of planets in the Solar System

Let us see how that works out in practice. You can see from this diagram that there is exquisite agreement between what is predicted, and what is observed.

Now, let us instead of considering the Sun, let us consider the Earth, where we know that at the surface the acceleration of the Earth is given by $9.8\ {}^{m}\!/\!{}_{s}\!/\!{}_{s}$. Therefore, now we can rewrite our force equation as:

$$F = \frac{GM_{\oplus}m}{r^2} = ma$$

$\oplus$ is just the symbol for our planet. Now if we have something like a piece of chalk, which is our *m*, we see that that will cancel from both sides of the equation, and so we can actually solve for the mass of the Earth.

$$a = 9.8\ {}^{m}\!/\!{}_{s}\!/\!{}_{s}$$

$$M_{\oplus} = 9.8 * \frac{r^2}{G}$$

2.1 Weighing The Earth

Therefore, if we know *G* and the radius of our planet, we have actually weighed the Earth. Sometimes we actually say that the determination of the gravitational constant is the weighing of the Earth. Now you can see that since:

$$r = 6 * 10^6 m$$
$$G = 6.7 * 10^{-11}(mkg)$$

The units of *G* are a little strange; therefore, I am just going to say that were in the MKS-system where we measure mass in kg here. We end up with the mass of the Earth being:

$$\begin{aligned} M_{\oplus} &= 9.8 * \frac{r^2}{G} \\ &= 9.8 * \frac{6 * 10^6}{6.7 * 10^{-11}} \\ &\approx \underline{5 * 10^{24} kg} \end{aligned}$$

2.2 Circular Orbits

Let us proceed to circular orbits. We know that the speed is **constant**. This allows us to **eliminate** the speed by considering an entire orbit of a body, say one star orbiting another more massive star. Since the speed is constant, we know that the velocity or speed in this case, if we ignore the direction for a moment, is given by an extremely simple idea. We just take the distance and divide it by the time, and we can choose any amount of distance and any amount of time, because the speed is constant, and, if we choose the complete orbit of the object, we get:

$$\upsilon = \frac{2\pi r}{t}$$

Where r now is the distance from one object to the other object, and $2\pi r$ is nothing more than the circumference of the circle. Therefore, it goes one complete revolution about its orbit in the time t, where t is the orbital period. Since we know, once again, that:

$$\upsilon^2 = \frac{GM}{r^2} \quad \text{with} \quad \upsilon^2 = \frac{4\pi^2 r^2}{t^2} \quad \text{and} \quad t^2 = \frac{4\pi^2}{GM} * r^3$$

Alternatively, in words, the square of the period is proportional to the cube of the radius of the orbit.

Now this only works for circles, actually at least we've derived it for circles, but in fact a similar equation can be derived for elliptical orbits, where instead of r we end up defining something called the semi-major axis of the orbit, but it works in any event.

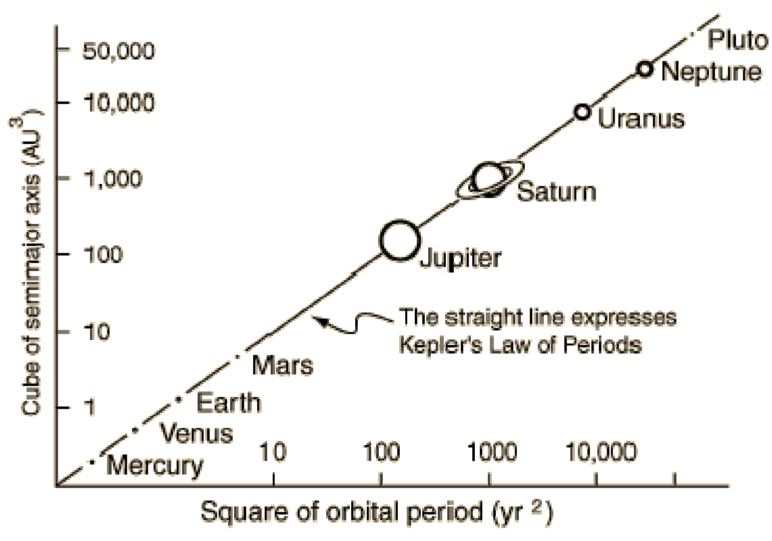
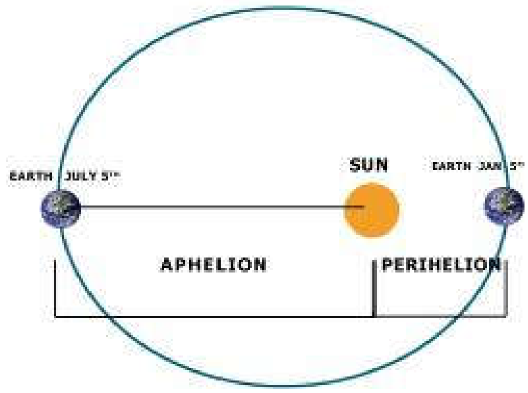


Illustration 44 : Demonstration of Kepler's third law

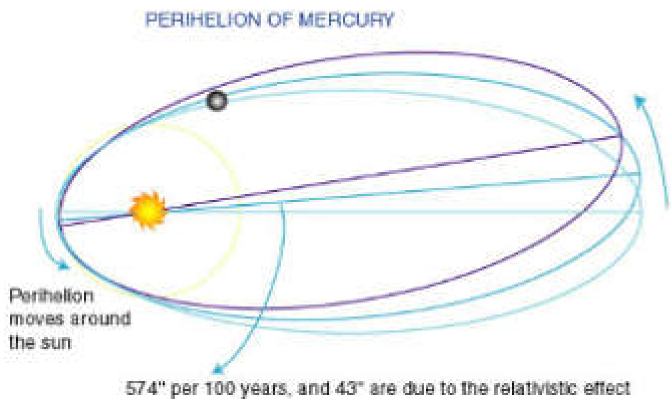
Let us see how this actually turns out for the planets in our Solar System. You can see here what that law looks like for every large body in the neighborhood of the Sun. Wow! Everything works! We are done. Problem solved!

Not quite!

After a while, we realized that something was not right. Mercury was not moving according to specifications, even when you included the ellipticity of the orbit, and all the gravitational effects of the other planets. The amount of the discrepancy was quite small, but it was real, since it was over 100 times more than the probable error associated with the data. It could not be ignored. Here is the crux of the situation.

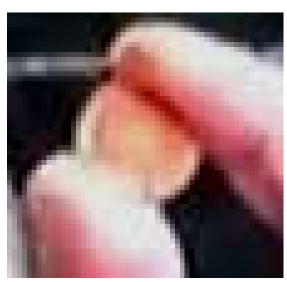


When you have an elliptical orbit, there is a point in the motion where you are closest to the sun. That is called the perihelion point.



The position of Mercury's perihelion was changing a bit more than Newton's law predicted. Here you see the situation.

How much was it off by?



You see this penny? If you held this penny up to the sky at a distance of about 100 m, the angle it would subtend would be equal to the discrepancy in Mercury's orbit over the period of 100 years. That is pretty amazing. Well, you might say since the discrepancy is so small, the correction to the law must be small as well.

Wrong!

This tiny problem, along with several others, lead to a profound change in our entire understanding of the structure of space, and how it affects the motions of all bodies in the universe. The important point here is that sometimes-incredible revelations can be the result of measurements that deviate so little, from what we anticipated. It is the job of the scientist to pay attention to these details, because on occasion these details can be the key to some overarching principal that would otherwise be overlooked.

Let us get back to this discussion, which in this case is using Newton's idea of mechanics, to yield insight into some cosmic X-ray sources. The summary of our results can be expressed in four very simple equations.

The first equation was that the speed of an object in its orbit is given by the circumference of its orbit.

$$\upsilon = \frac{2\pi r}{t}$$

Equation 7 : Orbital speed

The second equation is nothing more than a restatement of Newton's second law.

$$\begin{aligned} F &= ma \\ &= \frac{GMm}{r^2} \end{aligned}$$

Equation 8 : Newton's second law

Third, we also know that for circular orbits the acceleration is given by:

$$a = \frac{\upsilon^2}{r}$$

Equation 9 : Acceleration in a circular orbit

Last but not least is Kepler's third law.

$$t^2 = \frac{4\pi^2}{GM} * r^3$$

Equation 10 : Kepler's third law

That is it!

These four equations allow us to do some incredibly interesting and beautiful things, and we are going to use these results to explore one of the most fascinating X-ray sources in the sky: Centaurus X-3.

3 Of Hummingbirds, Trains And The Doppler Shift

As I have emphasized before we astronomers have some tremendous problems on our hands. We cannot just vary our experimental domain. We have to accept the universe as given to us, but it is quite remarkable that we can find out so much about the cosmos that we inhabit. We have seen that just being able to find out where objects are in the sky, and how far they are away from us was an extraordinary achievement, especially for X-ray astronomy. Certainly, a next logical step would be to find out how these objects are moving. To do this requires some knowledge about their velocities, and this is what we shall explore here.

Let us consider a moving object, and let us imagine that the object is emitting something periodically. It could be light waves, it could be sound waves, or it could be just some ticking of a clock. A moment thought would show that: if you are in front of the object, and, therefore, the object is approaching you, you will see the phenomenon a bit more frequently than if the object were stationary. This is because, if the object is moving towards you, each pulse or wave will have less distance to travel to get to you, because the object's motion will be decreasing the distance between you. Hence, the time interval that you measure between the pulses will be shortened.

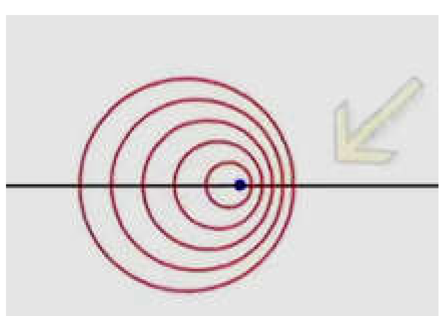


Illustration 45 : Pulses around a moving object

This is easy to see here. You can see that the pulses sort of bunch up in front of the object and seem to be more spread out behind. Therefore, if you measure the time of arrival of these pulses they will be more frequent if the object is approaching you and less frequent if, it is moving away.

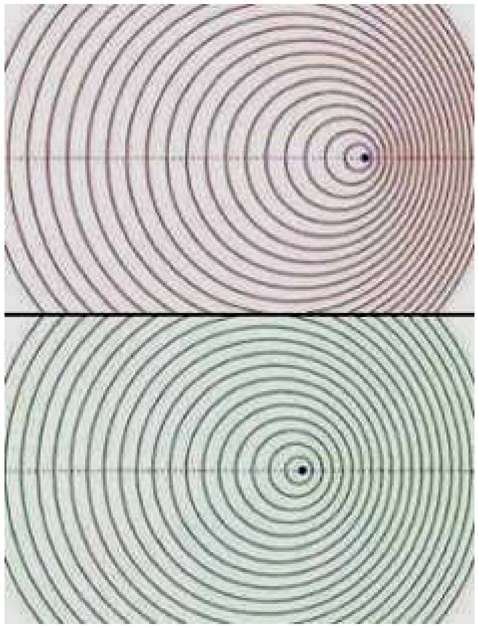


Illustration 46 : Pulses around a two moving objects with different speed

Furthermore, you can see that the faster the object is moving, the more the frequency will change. Here you see a comparison of two objects, the top one of which is moving faster than the bottom. Let us see if we can do some experiments to detect this phenomenon, which is known as the Doppler shift in honor of the Austrian physicist Christian Doppler, who proposed it as a possibility way back in 1842.

At this point, please watch "Analyzing the Universe005.mp4"

Video 5 : Hummingbirds & passing train

A remarkable property of the Doppler shift is that for speeds that are small compared to the propagation speed *c*, which is the speed of sound in the case of sound, the speed of light in the case of light, the changes that occur have the same mathematical form even though the nature of sound and light are quite different. In all of these cases, you get the following.

$$\frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$$

If you are measuring the wavelength of sound or light, the change in frequency over the stationary frequency is the same.

$$\frac{\Delta f}{f} \approx -\frac{v}{c}$$

Therefore, this is what you would use if you were measuring the frequency of light or the pitch of a sound. If you are measuring the time of arrival of a sound pulse or a flash of light:

$$\frac{\Delta t}{t} \approx \frac{v}{c}$$

In all these cases, v is positive if receding from you, and in all cases v has to be much, much less than the velocity of propagation.

However, there is one problem with this. If the velocity is across your line of sight, instead of towards you or away from you, you get nothing, nada, zero. We must amend this, and realize that it is only radial motion that exhibits this phenomenon. Therefore, let us just put:

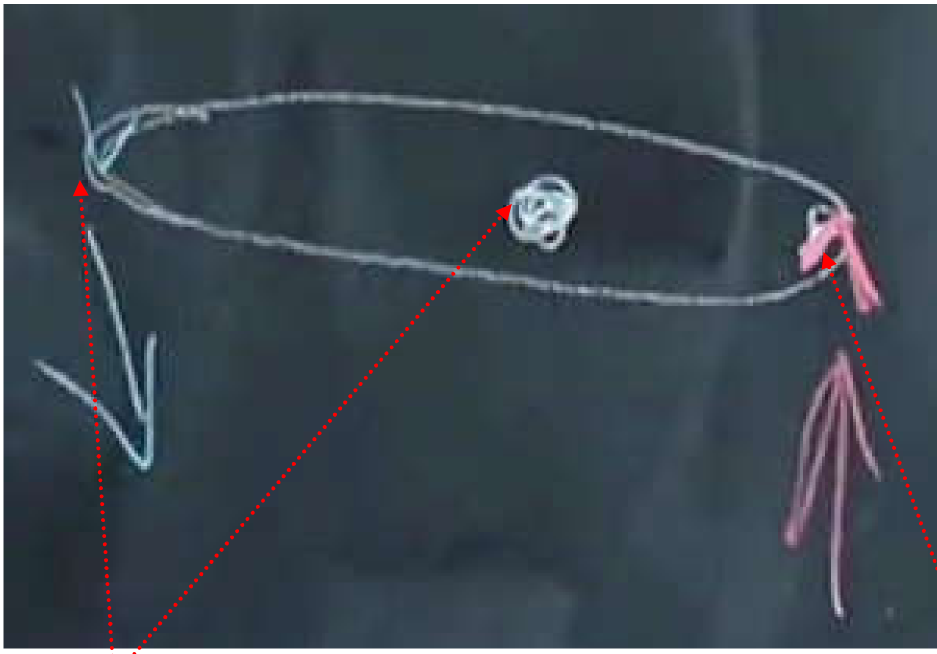
$$\frac{\Delta\lambda}{\lambda} \approx \frac{v_R}{c}$$

$$\frac{\Delta f}{f} \approx -\frac{v_R}{c}$$

$$\frac{\Delta t}{t} \approx \frac{v_R}{c}$$

R here to shows that it is only back and forth motion that the Doppler shift can tell us about.

This is another possible bummer. You might think, now, this is useless. If, for example, we have a binary star whose orbit is in the plane of the sky, then the motion will be invisible to us. Therefore, if a star is going around another, the motion will not be visible. Now, sometimes we get lucky. Imagine the plane of an orbit, which is perpendicular to the plane of the sky. This might look like this.



Our central object is here and our orbiting objects kind of goes around it. May be receding in this direction here and approaching in this direction here. Now you can see that the motion of the star revolving around its companion exhibits a maximal effect at the sides, with one side approaching and one side receding from us. When it is moving across our line of sight, we should see no effect at all. We should observe just the same thing as if the object were not moving.

Does this ever happen? Well, fortunately for us many X-ray sources are binary stars with very short orbital periods. Remember that Kepler's law that said:

$$T^2 \propto r^3$$

Small *T* means the distance between the stars is relatively small, and that means that there is a good probability that we might catch some edge-on enough to undergo an eclipse. If they are edge-on, then the velocity we measure at the extremes of its motion towards or away from us is a good approximation to the circular velocity throughout the orbit.

How can we detect this possibility? Well, look at this video clip and see.

At this point, please watch "Analyzing the Universe006.mp4"

Video 6 : Doppler shift and light intensity

Potentially we have a goldmine here.

Can we plumb its depths? The answer is a resounding yes. In the early 1970^s, using data from Uhuru, the first dedicated satellite devoted to X-ray astronomy, Ethan Schreier and his coworkers discovered a remarkable X-ray source that brought together almost all the ideas that we have studied to date. By looking at power spectra, light curves, energy spectra, and other aspects of the data, we were able to construct a model, positively breathtaking in its completeness. We learned so much about this object with such exquisite accuracy that you would have thought that it resided around the corner from you, instead of at a distance of about 30,000 ly. Thus, the X-ray light that Uhuru collected from this object in the 1970^s began its lonely trip to the Earth some 30,000 years ago, and in the following lectures, we will explore it.

4 Clocks In The Sky — Cen X-3

4.1 EXOSAT

Timing is everything. Our ancestors' very survival depended upon it. Knowing when to plant crops, when to move their living quarters to lower elevations, or when animals they hunted began the migration to different feeding grounds. When the earliest humans realized that certain recurring star patterns at night presaged the return of spring and the planting season or the onset of fall and the harvest season, they had discovered in effect that the Earth makes a trip around its parent Sun once every 365 or so sunrises. Many cultures divided this year into smaller units based on the recycling of phases of the moon, and then into still smaller ones, such as our presently used weeks and hours.

Galileo and his contemporaries learned to use pendulums and water clocks to fine-tune timing to units of seconds. Their successors in today's modern laboratories have created atomic clocks that can pin down time intervals that are smaller than a nanosecond, 10^{-9} s. And just as there are clocks in the sky that have long periods, like the Sun, the Earth, and the Moon, motions that govern the year, the day, and the month, there are other celestial clocks which have much smaller periods. These clocks were only discovered by astronomers after the construction and perfection of short period clocks on Earth. Some stars pulsate; expanding and contracting regularly with periods that are only minutes long. Others take years to complete one cycle. All stars rotate, just as the Earth does, with periods that range from ms to months. Binary system contains two stars that mutually orbit in regular period of days to years. Clocks indeed can be found in almost every variety through out the sky.

One of the most astonishing discoveries of the 20th Century along these lines occurred in the late 1960^s, when Jocelyn Bell, then a graduate student in Cambridge, England, discovered a source of radio waves in the sky that seemed to be changing its brightness every 1.337 s. Furthermore, the period of the brightness variation was precisely repetitive to better than 1 : 10,000,000. Such a stable celestial clock was unheard of, and the discoverers jokingly referred to the new signals as originating from little green men. However, soon thereafter, many such sources were discovered, and the LGM's seemed to be begging for another explanation, renamed Pulsars. They are among the most intriguing cosmic sources of radiation we know. They have extremely well-defined periods, making exceptionally accurate clocks. For example, the period of Pulsar 1937+214 has been measured to be 0.00155780644887275 s, a measurement that challenges the accuracy of the best atomic clocks we have here on the Earth.

How can something change its brightness almost 1,000 times each s?

It turns out that these objects are not pulsating at all, but are incredible stars that rotate 1,000 times each s. These stars are so dense and compact, that one thimble full of material from their surface would weigh as much as millions of full-sized African elephants. Their extremely large gravitational fields prevent them from breaking apart, and their light variations are due to beacons somewhat similar to those of lighthouses that beam radiation in a search light fashion as they rotate. Because these compact objects are small and have intense gravitational fields they can accelerate materials to very high speeds.

When this material collides with some neighboring gas, the object can heat up to millions of °C. This leads to emission of X-rays, and, indeed, some of the most exciting discoveries concerning the nature of white dwarves, neutron stars, and black holes, have been made by looking at X-radiation using satellites such as CHANDRA. Let us look at one of these sources in depth.

Cen X-3, discovered more than 30 y ago, beautifully illustrates the process of astronomical discovery, and is a representative of an object of this kind. Using X-ray and optical data, we can reconstruct the contents, properties, and behavior of the entire system. We can determine that Cen X-3 is a binary system. That it contains a Neutron star, and a companion much larger and more massive. We can find the rotation period of the Neutron star, the orbit size of the Neutron star; the size and mass of the companion star, the luminosity of the source, which turns out to be thousands of times brighter than the Sun, and much more. Not only can we tell the size of the objects using clocks, sometimes we can also deduce their ages. These objects are like huge flywheels, storing vast quantities of rotational energy. Let us look in detail at Cen X-3, and see how we can piece together the observations to understand this fascinating system.

At this point, please watch "Analyzing the Universe007.mp4"

Video 7 : X-3 observation

It is not quite constant, and if we follow the values of our new clock, which corresponds to a period,

$$P = {}^{1}\!/_{f}$$
$$P_1 = 2.09d$$
$$P_2 = 4.836s \text{ to } 4.822s$$
$$f_1 = 0.2068\,/\,s$$
$$f_2 = 0.2074\,/\,s$$

Now these two are different periods, right?

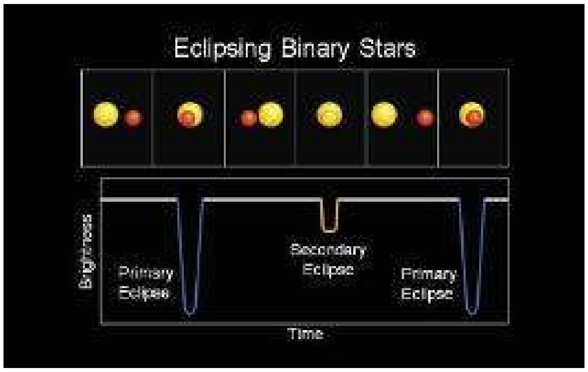
This is a 2 d period, and this is going to correspond to something else within the star. We get for these periods of about 4.836 s to 4.822 s. In addition, let us see, this is the larger frequency; therefore, it corresponds to the smaller period. I think I might even have that right, but you can check me on that. It is changing its frequency.

In addition, guess what? It does so smoothly, varying back and forth over, what do you think the time period is?

Right, 2.09 d. We have apparently uncovered a classic case of an eclipsing binary star. However, wait just a cotton-picking minute.

If every 2.09 d we really see an eclipse that lasts about 40,000 s, can we predict anything from this observation?

Sure. If the X-ray emitting object is going in, and then coming out from behind another star, as it does so, maybe we should see a change in the X-ray energy spectrum, similar to the way the Sun and sky changes color at sunrise and sunset, as the sunlight passes through more and more of the Earth's atmosphere. Therefore, the picture is this.



We have an object, and we have our X-ray source that goes behind the object, and then comes out of eclipse. As it goes through the limb of our companion star, and as it comes out from the other limb of the companion star, it is possible that the energy that we see from the X-rays will change its composition, just as the sky changes to red during sunrise and sunset. In addition, indeed, although the mechanisms are very different for X-rays, the result is that we do see the source change as it goes into and out of eclipse. Therefore, we are beginning to put together a satisfyingly coherent picture of our system. A source of cosmic X-rays, which somehow has an internal clock of about 4.8 s, is orbiting another object every 2.09 d.

However, what are these objects, and what is the 4.8 s periodicity due to?

Well, let us roll up our sleeves, and get back to work. Let us examine what we already have, and where it can get us. First, it appears that the regularity of our range of different periods is due to the Doppler shift of the X-ray emitting star travelling around its companion. Since

$$\frac{\Delta f}{f} = \frac{|\nu|}{c},$$

and our range in frequencies is 0.2074 - 0.2068 Hz. We end up with:

$$\begin{aligned}\frac{\Delta f}{f} &= \frac{|\nu|}{c} \\ &\approx \frac{(0.2074 - 0.2068)/2}{0.2071}\end{aligned}$$

See if you can understand why there's a factor of 2 in there. That means that: $\frac{|\nu|}{c}$ is equal to, and we probably should put in approximately equal things, just to show that we are really not exactly 100 % accurate here. This is going to be equal to $\approx \frac{0.0003}{0.2071}$, and that equals approximately 0.00145. Therefore, when we solve for υ, υ turns out to be around 430 $^{km}/_{s}$ if we have a circular orbit, and, in fact, these objects really are mostly in circular orbits, because of other factors of their orbital circumstances.

Now we can find the size of the orbit. Since the circumference of the orbit must be equal to $2\pi r$, the object goes around at a radius *r* from the companion, it goes once around, and if the speed is constant at 430 $^{km}/_{s}$, that distance is nothing more than the velocity times the amount of time it takes to go once around, namely 2.09 d. Therefore, now we can figure out what *r* is.

$$\begin{aligned} r &= \frac{\nu T}{2\pi} \\ &= \frac{430\, {km}/{s} * (2.09d * 86{,}400s)}{2\pi} \\ &= \underline{1.236 * 10^7\, km} \end{aligned}$$

This is about ¼ the size of Mercury's orbit around the Sun. Therefore, these two objects are really close together. Now we can do something really neat. Since the X-ray source is eclipsed for about 40,000 s every orbit, we can estimate crudely the size of the other object. Just take for its diameter that 40,000 s worth of blackout, and multiply by the speed that the neutron star is going as it goes around in its orbit.

$$\begin{aligned} d &= 430\, {km}/{s} * 40{,}000s \\ &= \underline{1.7 * 10^7\, km} \end{aligned}$$

This would be a crude estimate of the diameter of our companion star. It is approximating the arc of a circle with a straight line. Therefore, the companion star's radius is about half that, or 8.5 * 10^6 km. Thus, not only is the orbit small, the X-ray source must be very close to the surface of the other star.

$$\begin{aligned} r_{orbit} &= 1.2 * 10^7\, km \\ r_* &= 8.5 * 10^6\, km \end{aligned}$$

What we are doing is we are imagining that we have a star, and that the object is just moving behind it, but in a straight line instead of a circle. It is actually not a really bad approximation. However, what it means is the radius of the star is over 10 times the size of the Sun. Now, I do have to say we did make some approximations here, and we talked about one of those approximations.

What are some of the other assumptions that we made?

In addition, I will leave that to you to figure out. Therefore, if our theory about the nature of the low state in Cen X-3's light curve is correct, we have a prediction. It is that the companion star should be quite large and massive.

Can we test that theory? Yes! Remember when we talked about gravity? We derived an equation relating the period of an orbit to its size, or radius. Better known as Kepler's third law, it states that the square of the period of an object in an orbit is proportional to the cube of the radius of that orbit or:

$$T^2 = \frac{4\pi^2}{GM} r^3$$

Now we know what T is, its 2.09 d. We know what r is, it is 1.2 * 10^7 km. We can solve for M. It turns out that our derivation of this equation is a somewhat simplified version of reality. In actuality, when you do a more precise derivation of this equation, the mass in the denominator here is really the sum of the two masses in the system, but this is really not a big problem at all. If we solve for M, you get, and I urge you to do this, about 3 * 10^{34} g, about 15 solar masses. This is an excellent problem with which to practice unit conversion; do it on your own. This result is reassuring. We see that the system is a massive one, which is what we suspected on the basis of the light curve analysis.

Meanwhile, on the optical frontier the hunt was on for the optical counterpart of our X-ray source. The difficulties were enormous. Centaurus is in a heavily obscured part of the Milky Way, and, remember, our early error boxes for locations of sources were quite crude. Therefore, despite our detailed understanding of the orbit based on the X-ray data, it was 3 years before we found this object optically, but the discovery was unmistakable. A Polish astronomer, Voytek Krisminsky, found a hot, massive star that changed its brightness ever so slightly every 2.09 d, in lockstep with Cen X-3's X-ray clips.

Why such a small variation?

Well, maybe Cen X-3 is very small; therefore, during its orbit Krisminsky's stars brightness does not change very much. Indeed, the situation is somewhat more complicated, but it is a good starting point, based on our understanding that GK Per had a white dwarf for its X-ray emitting component. Come to think of it, let us check to see if a white dwarf can be responsible for Cen X-3 X-ray output. If it is a white dwarf spinning around every 4.8 s, we know that its speed on the equator must be:

$$V = \frac{2\pi r}{T}$$

Where r is now the radius of a white dwarf, about 6 * 10^8 cm, and T now is 4.8 s. Right, it goes once around on the equator, traveling $2\pi r$, and it does so in 4.8 s; therefore, the velocity just distance divided by time. In other words, we have an Earth-sized object, spinning around every 4.8 s. If we solve this for V, we get:

$$V = 8 * 10^8 \, {}^{cm}\!/_{s}$$

Therefore, the acceleration we would feel, trying to pull us off the star, due to its rotation, would be:

$$\begin{aligned} a &= \frac{v^2}{r} \\ &= \frac{64 * 10^{16}}{6 * 10^8} \left[\frac{cm}{s^2}\right] \\ &\approx 10^9 \left[\frac{cm}{s^2}\right] \end{aligned}$$

Is gravity up to this task? Can it pull us in from the surface of a white dwarf with enough acceleration so that we would not fly off due to the acceleration that is trying to get us to go away from the center of the star?

Let us see what a one solar mass white dwarf has for its gravitational acceleration.

$$\begin{aligned} a_G &= \frac{GM}{r^2} \\ &\approx \frac{6.7 * 10^{-8} * 2 * 10^{33}}{\left(6 * 10^8\right)^2} \left[\frac{cm}{s^2}\right] \\ &\approx \underline{4 * 10^8 \left[\frac{cm}{s^2}\right]} \end{aligned}$$

Uh-oh, we are in trouble. This second number is smaller than the first number. Gravity cannot prevent a white dwarf from just flying apart due to its spin.

What do we do now?

Well, fortunately since Jocelyn Bell's discovery of the radio pulsars a few years before, we had a fairly good idea about what the solution might be. Neutron stars, a new type of object in the cosmos, or at least our understanding of it, would fit the bill. This story actually begins with the white dwarfs, and with Subrahmanyan Chandrasekhar, a truly wonderful man with whom I was fortunate enough to spend several days when I was a graduate student at Princeton, and incidentally after whom the CHANDRA X-ray satellite was named. In 1930, Chandrasekhar, at the age of 19, discovered that there was a limit to the size of a white dwarf. If such a star had a mass in excess of about 1.4 solar masses, it simply could not resist the pull of gravity and must collapse. It had no choice. This was initially met with derision on the part of most astronomers.

Where would the star go? Would it disappear?

Well, the universe seems to be ultimately impervious to prejudice. Just 4 y after Chandrasekhar put forward his bold idea Walter Baade and Fritz Zwicky proposed the existence of a neutron star. If the white dwarf had to collapse, the electrons would be the first to go, and the star would consist essentially of a giant nucleus. The neutron had just been discovered a year earlier by James Chadwick; therefore, slamming an electron into a proton to form a neutron seemed at least plausible.

However, was this not preposterous?

Nuclear densities without the support of the vast empty space between it, and the electrons would mean that a teaspoon full of this star; remember our teaspoon?; remember our white dwarf?; would weigh about $5 * 10^{11}$ kg. This is just a number.

What does it mean?

It is a big number. Well, a typical African elephant weighs about $5 * 10^3$ kg; therefore, our teaspoon full of this neutron star stuff has the same mass as about 100,000,000 African elephants. **Absolutely astounding.**

However, how does this solve our Cen X-3 problem?

Well, the radius of this star, according to a calculation that you can and should do by simply scaling up a neutron to the mass of our star, would be about 10 km, about half the length of Manhattan island. Oh, I know that Manhattan is not circular or spherical, but you get the idea, right? Let us imagine a two solar mass neutron star, the radius of which is 10 km.

Would gravity be sufficient to hold this star together?

Let us find out. With a period of 4.8 s, and a radius of 10 km, the speed of a test mass on the equator of the star would have the following velocity:

$$\begin{aligned} \nu_* &= \frac{2\pi r}{T} \\ &= \frac{2\pi 10^3 m}{4.8 s} \\ &\approx \underline{1.3 * 10^6 \left[\frac{cm}{s}\right]} \end{aligned} \qquad \begin{aligned} a &= \frac{\nu_*^2}{r} \\ &= \frac{\left(1.3 * 10^6\right)^2}{10^6} \left[\frac{cm}{s^2}\right] \\ &\approx \underline{\underline{1.7 * 10^6 \left[\frac{cm}{s^2}\right]}} \end{aligned}$$

Now, once again, we compare this to the acceleration due to gravity:

$$a_G = \frac{GM}{r^2}$$
$$\approx \frac{6.7 * 10^{-8} * 4 * 10^{33}}{10^{12}}\left[\frac{cm}{s^2}\right]$$
$$\approx 2{,}7 * 10^{14}\left[\frac{cm}{s^2}\right]$$

Yes, no problem. The acceleration due to gravity is much, much stronger than the acceleration trying to get the star to fly apart. This is no problem, but an astonishing number anyway. What this means is that if an object were dropped at a distance of 1 m from the surface of such a neutron star, it would hit the surface in about a millionth s, and it would arrive at the surface traveling almost 3,000 $^{km}/_{s}$. Calculate what that is in $^{mi}/_{h}$.

However, what exactly is it that provides our clock?

It turns out that the most likely possibility is similar to what causes aurora on the Earth. In that case, charged particles from the sun are funneled into the magnetic polar regions of our planet where they collide with each other, and give rise to spectacular light shows. We believe that this is likely to happen in the outer reaches of a neutron star's environment as well. Material form the companion star is concentrated by the magnetic field of the neutron star, and this, coupled with the intense gravitational field, heats up the gas to incredible temperatures. If the rotational axis is inclined to the magnetic field, similar to the way that the Earth's magnetic poles are not coincident with the geographic North and South poles, we have a natural way to provide a beacon of light that we can see every 4.8 s. Essentially, the magnetic poles become hot spots that radiate copious amounts of X-rays, because of the tremendous amount of gravitational energy that can be converted into light.

At this point, please watch "Analyzing the Universe008.mp4"

Video 8 : Light pulses by a neutron star

4.2 CHANDRA

Now, let us go one-step further, and revisit Cen X-3, 15 years after the EXOSAT observation we just examined, and see what CHANDRA can add to the picture.

At this point, please watch "Analyzing the Universe009.mp4"

Video 9 : CHANDRA observation of Cen X-3

Therefore, *f* for CHANDRA it is centered on a frequency equal 0.2080 /s, or a period of about 4.81 s instead of our frequency with EXOSAT, which was about 0.2071 /s, for a period with EXOSAT of about 4.83 s. There is a clear difference here. It is a small amount, but look at the power spectra of these two satellite observations side by side.

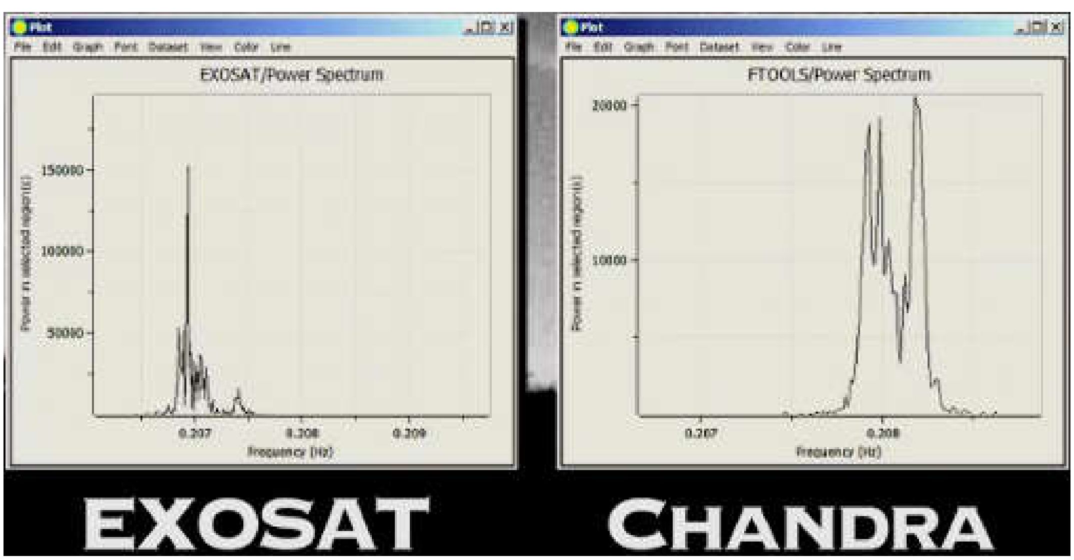
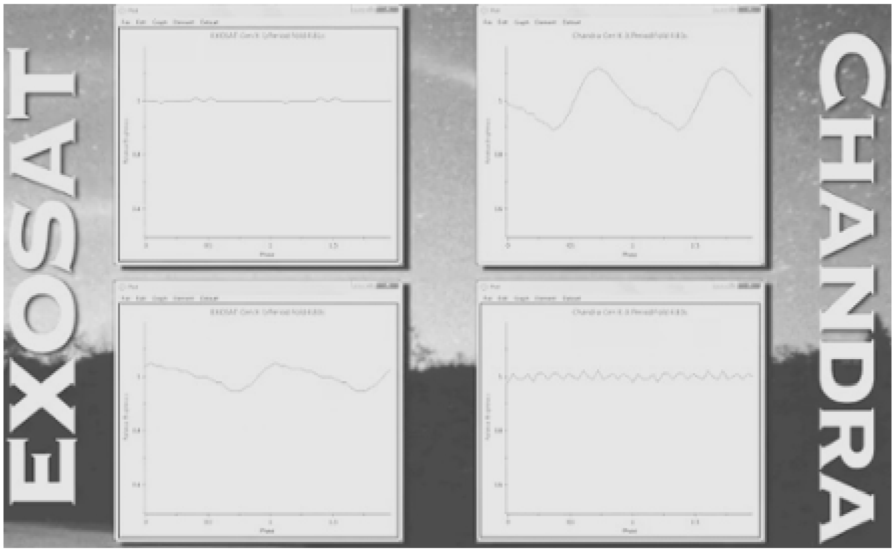


Illustration 47 : Comparison of power spectra of Cen X-3 from EXOSAT and CHANDRA

It is so small, maybe it is insignificant, but just as we did a period fold with GK Per we can do it with Cen X-3. I urge you to do this on your own. It is a lot of fun using DS9, but I will show you just the results here.



You can see that with a 4.81 s fold, the EXOSAT data is just flatter than a pancake. With a 4.83 s fold, the CHANDRA curve shows no variability. The effect is real. What this means is Cen X-3 has spun up in 15 years; it is going faster. In addition, in fact, when you look at it over even longer time spans, it seems relentlessly and predictably gaining speed in a more or less linear fashion.

What could be causing that?

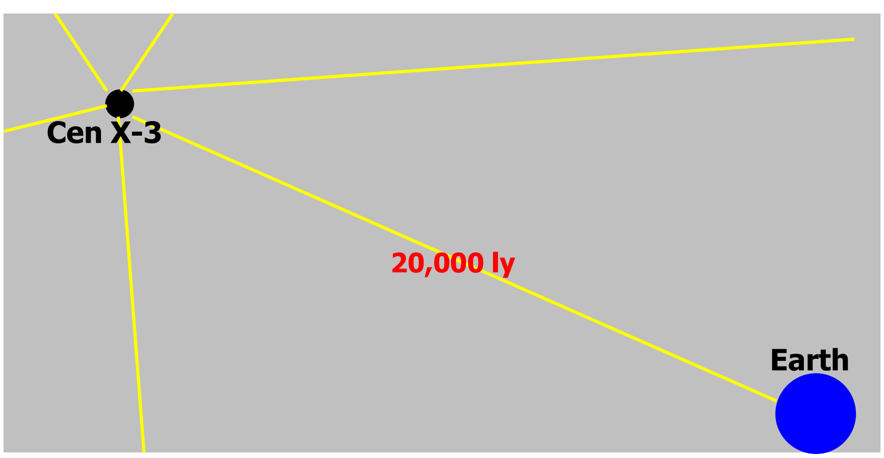
Well, it appears that the companion star feeds the X-ray source some material, and as that gas gets closer and closer to the neutron star, it gives the star a bit of a kick. It is quite similar to what happens when an ice skater does a spin, and draws in his or her arms. They spin faster and faster and faster to conserve angular momentum.

One more interesting thing we can do is to find out the luminosity of this object in the X-rays. From the optical brightness and spectrum of Krzeminski's star, we have deduced that the distance to Cen X-3 is about 20,000 ly. Now, from the X-ray observations we can find the average flux, or the amount of energy that passes through each cm^2 of our satellite's detector each second. To do this, we return one last time to DS9 and examine Cen X-3's energy spectrum.

At this point, please watch "Analyzing the Universe010.mp4"

Video 10 : Energy flux of Cen X-3 by CHANDRA data

The flux is $2.4 * 10^{-9}\, erg / cm^2 / s$. This means that every cm^2 area at the distance of the Earth from Cen X-3 receives about $2.4 * 10^{-9} erg$ of X-rays each second. If Cen X-3 radiates isotropically, which is a highfalutin word for uniformly 'in all directions', which means we can take this number and multiply it by $4\pi r^2$ to find out the luminosity of Cen X-3, where *r* in this case is 20,000 ly.



Basically, what is happening is that Cen X-3 is putting out light in all directions, a little bit of which gets to us. In addition, if it is at a distance of 20,000 ly, you can see that each second the light from Cen X-3 will fill up a ball whose surface area is $4\pi d^2$. Therefore, all we have to do is take the flux, which represents 1 cm^2 of area, and multiply it by all of these other cm^2 where our satellite is not. However, which if we did have something to detect Cen X-3, we would see the same thing as we do here near the Earth. Thus, the luminosity is:

$$L = 4\pi d^2 * f$$

If we do that with d = 20,000 ly, we multiply our flux by the cm equivalent of 20,000 ly, and if you do that, converting ly to cm, you get the luminosity of Cen X-3 is about $1.3 * 10^{37}\ {}^{erg}/_{s}$. This is about 3,000 times the entire energy output of the Sun, and all this from an object whose radius is no bigger than ½ the length of Manhattan Island.

Therefore, we have come full circle. It appears that the precisely varying X-rays we see in Cen X-3, GK Per and other compact X-ray binaries are rotating hotspots associated with the star's magnetic field. Over the years, we have discovered many such sources, each with a unique set of orbital circumstances, and each with its own characteristic idiosyncrasies. Indeed, we have just scratched the surface of the wonderful world of X-ray binaries. Many surprises were in store for astronomers over the past 40 years, and many more undoubtedly will come in the future. Now it is time to move on and explore an entirely different class of objects. Stay tuned as we examine our cosmic recycling centers, supernova remnants, which are the products of the most dramatic and energetic explosions that our universe has to offer.

Supernova, Our Cosmic Recycling Centers

1 Cosmic Recycling Centers And Cas-A

The poets and songwriters have always characterized the heavens as unchanging. The stars are immortal, in contrast with the ordinary life processes on Earth. Daylilies and butterflies may be fleeting, but the Sun and stars will endure. However, even the stars go through definite life cycles, and their story is a fascinating one. After all, every single atom of Ca in every bone in our bodies was produced inside an ancient star, which then exploded and added the processed material to the interstellar medium, some of which later went into forming our Sun, Earth, Solar System, and finally us.

Astronomically in human terms, the story begins a mere 75 years ago. Scientists at that time had no real understanding of the energy sources that allowed the stars to shine. All the known possibilities from chemical reactions, like burning wood in a fire, to utilizing gravitational potential energy stored in the star. In other words, having the star contract to smaller and smaller sizes as it radiated, fell woefully short of the required energy. All these energy sources could power the stars for a mere 1,000 to possibly 10,000,000 years. However, our knowledge of the age of the rocks and the Earth indicated several billions years of existence for the sun. A crisis inevitably ensued.

Hans Bethe, working at Cornell, showed that nuclear physics provided the missing link in the chain of knowledge, which now describes the structure and evolution of the stars. Therefore, many observational puzzles have been explained, once the hypothesis of nuclear burning was adopted, that there can be scarcely any doubt that these enormous balls of fire and gas are powered by insignificant sub-atomic particles so small that it would take about 1 trillion of them, lined up end to end, to span the head of a pin. The universe is indeed a miraculous place.

The immense energies provided by the nuclear furnaces in the cores of stars are the result of one-way transmutations of elements, beginning with H to He. It is this processes, which cause the stars to evolve. As the star cooks the elements from H to He, to C and O, here is progressively less and less energy available to extract. Once the core of the star reaches Fe, the jig is up. No longer can the star replenish its expenditure of radiation, and it must change its structure radically. Depending on its mass, it can either cool down gradually, eventually dying like an ember in a fire, or go out in a blaze of glory with an utterly catastrophic explosion, becoming a supernova. During this explosion, which lasts only minutes, the released energy is so great, that for a short while the star outshines the entire galaxy of which it is part. Imagine an object shining brighter than the Sun by 100 billion times.

Although the actual explosion lasts for less than a day, the effects linger for centuries. The gas from the explosion hurtles outward at speeds approaching that of light, and it begins to plow through the space between the stars. We can see the accumulation of material, called a supernova remnant, still expanding today, even when the original explosion occurred thousands of years ago.

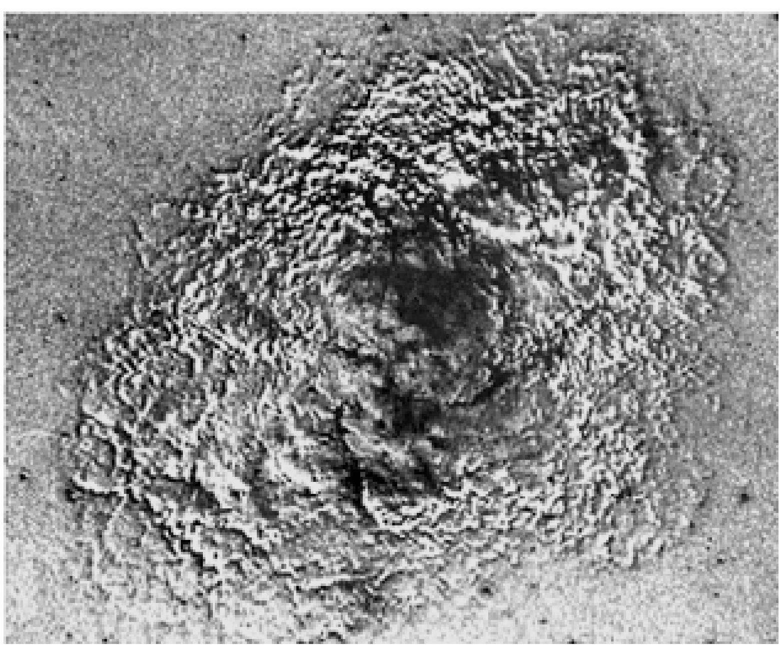


Illustration 48 : Changing in Crab Nebula

Here you see a remarkable double exposed photograph of the Crab Nebula, which was first visible in the skies of 1,054 A.D. One image was printed as white, the other, taken 14 years later, was printed, and superimposed black. You can almost feel the seething cauldron as it hurdles through interstellar space.

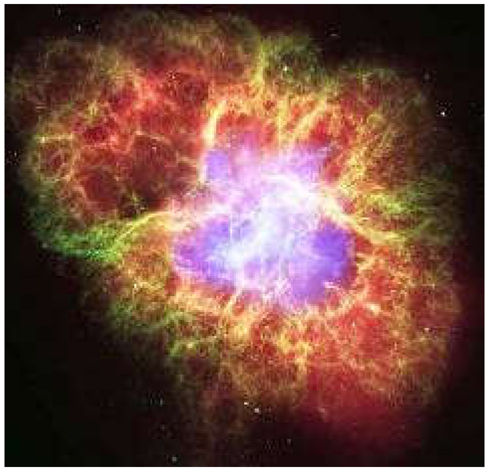


Illustration 49 : Composite photo of Crab Nebula

Here you see a composite photo of the same object, using a CHANDRA X-ray observation shown in blue, a Hubble optical observation shown in green, and a Spitzer infrared observation shown in red. The engine that powers these nebulae is often quite active, too.

At this point, please watch "Analyzing the Universe011.mp4"

Video 11 : Slow-motion of Crab Nebula

Often the explosion leaves behind a strange object. The very center of the region does not disperse, but forms a neutron star. We met this kind of object further in a different context when we examined Cen X-3. This is a star that has more mass than the sun, but occupies a volume no bigger than the city of Boston. Its density is truly astounding. One thimble full of its material would weigh as much as millions of full-sized African elephants. It usually spins on its axis 10 – 100 $^{1}/_{s}$ and it is called a pulsar. Even though it does not pulse at all, but as we have seen rotates instead. As the pulsar spins over the centuries, it adds electrons and other charged particles to the interstellar soup, and provides the energy we see radiating towards us today, from parts of the remnant. Since such high energies and temperatures are involved, it is not surprising that these supernova remnants can radiate copious amounts of X-rays. The pictures we get from these objects tell us many things.

Not only do we get an idea about the star that exploded, we also find out much about the interstellar medium itself, as the star's energy sweeps up and accelerates the once calm environment surrounding the star. The more detailed the picture we get from these objects, the better our understanding. Therefore, we try to get data from all parts of the electromagnetic spectrum, including X-rays. As we have seen, the problem is that X-rays are hard to focus, but about 20 years ago, we learned how to use grazing incidence mirrors for this purpose. The results were astonishing, and the improvements kept coming until now we have the superb optics of the CHANDRA satellite. We have looked at the CAS-A image before in DS9 several times, now we want to explore some of the physics that give rise to this incredible picture.

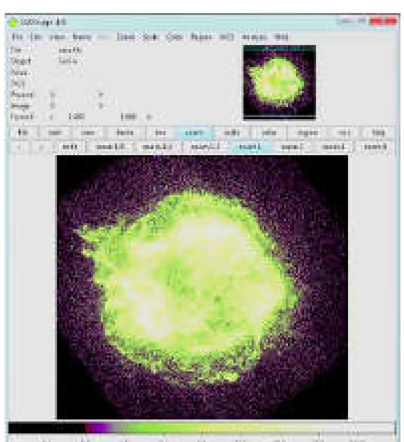


Illustration 50 : DS9 interpreted data from Cas-A

Here we see the display of our image set to emphasize the following discussion. I urge you to play around with DS9 using Obs-ID 114, which is the first data set listed when you initialize the virtual observatory. First, you see portions of a rotated square, which shows you the extent of the CHANDRA satellite's field of view. In addition, you see a very bright, almost white, and lumpy, but somewhat circular region surrounding a central point-like object. Outside the lumpy region, we see a fainter, wispier region.

What is all this telling us?

We have pieced together the following story. About 300 years ago the star, that is now the central object, exploded. Remarkably, this conflagration was not seen by anyone apparently. Even though these explosions, as we have seen, are usually large enough so the radiation can provide enough light for reading, even at midnight.

How then do we know when it happened?

Optical data shows material, via the Doppler Effect, streaming outward from the object at thousands of $^{km}/_{s}$. If we run this expansion backwards, the material would get back to the center in about 350 years, thus the object should have been visible around 1,650 A.D. Since this remnant has been expanding for over 300 years at an incredibly high speed, by now it is quite large. As is usual with astronomical objects, distances to supernova remnants are very difficult to determine. The best estimates come from the fast moving knots of material that we can actually see moving outwards through the sky over a period of years. We have just seen an example of this in the Crab Nebula. In the case of Cas-A, the bright spots you see in the X-ray image are examples of some of these knots. If we know how fast the knots are moving through space, Doppler shift again, and we know how far they move in angular extent across the sky, we can compute the distance to them.

The bright, almost circular ring that we see in this image of Cas-A is the current position of the shock debris from the explosion. In reality, it is a large hollow shell with very little material in the interior region near the pulsar, since the explosion has swept up the material much like a snowplow does when it drives through snow. Because the material is moving so rapidly that a shockwave forms. We see this as a faint outer shell outside the main ring of ejecta. The jet like structure, visible on the left-side of the remnant, may indicate higher velocity material rushing outward through a rarefied part of the interstellar medium. If you look carefully at the shape of this jet, you can see that, when you follow it back towards the center of the remnant, it seems to be aligned with that faint little dot; the central object in the very middle. You will see that the intensity of the remnant steadily increases from the center until about 100 arcs in radius. Thereafter, the remnant gets weaker and weaker. This is what you might expect for a more or less hollow ball with a dense outer shell.

In fact, the exact nature of this emission and its morphology, or shape, is a subject of intense research currently. By looking at profiles like these astronomers hope to gain some insight into the nature of the original explosion, and better understand the mechanisms by which the shock fronts form and travel through space.

The best however is yet to come. Some of the most exciting data from this object concerns the energy spectrum of the X-ray light from different parts of the remnants. Just as a blue flame is hotter than a red flame, and Na vapor lights are yellow, while Hg lights are blue, X-rays can tell us about the state of the emitting regions, and what substances are present in each part of the object. When you look at the energy of all of the X-ray photons that CHANDRA can collect from Cas-A, a remarkable picture emerges.

Superimposed on a continuous background of X-ray light we detect the fingerprints of the elements. Like that, prism that takes sunlight and makes a rainbow out of what we think is only yellow light from the sun, so are the detectors on CHANDRA examine X-rays. In addition, just as that rainbow contains information about the chemical composition of the sun, so the CHANDRA energy spectrum tells us about the recycled material from our supernova. It is all there. The building blocks of life, Ca, O, Fe. Let us go to DS9 and check this out.

2 Color It X-Ray

At this point, please watch "Analyzing the Universe012.mp4"

Video 12 : Color it X-ray

To The Ends Of The Universe; Quasars, 3C273 And Beyond

1 The Time Machine

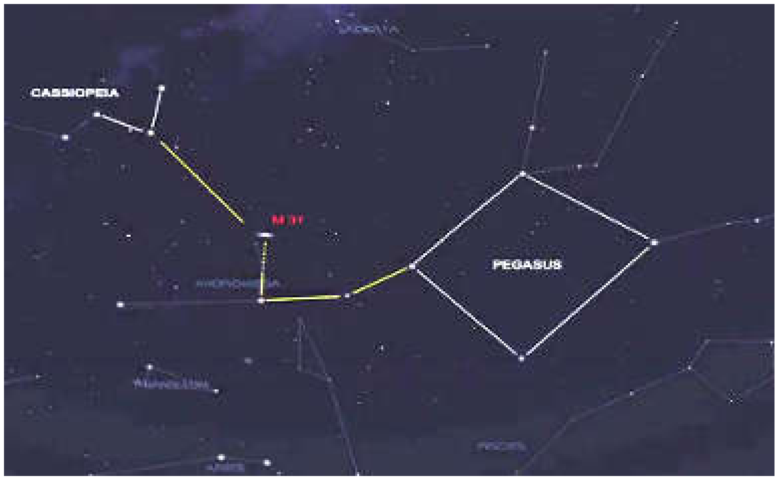
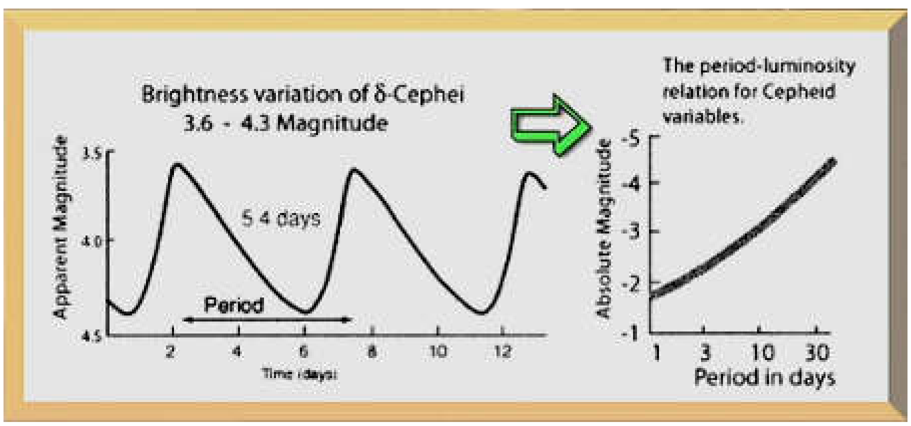


Illustration 51 : Location of M31 (Andromeda galaxy)

One of the most remarkable and useful characteristics of our universe is that as we look out into space, we are also looking backwards in time. Light travels about 186,000 mi in 1 s. When we look at the sun, whose distance is about 93,000,000 mi, we are seeing it as it was about 8 min ago. Thus, our astronomical observations can yield a history of our universe by examining objects very far away. However, we had no idea of the vastness and hence antiquity of the universe until the 1920s, when Edwin Hubble discovered some innocuous appearing stars in a nebula or cloud called M31.

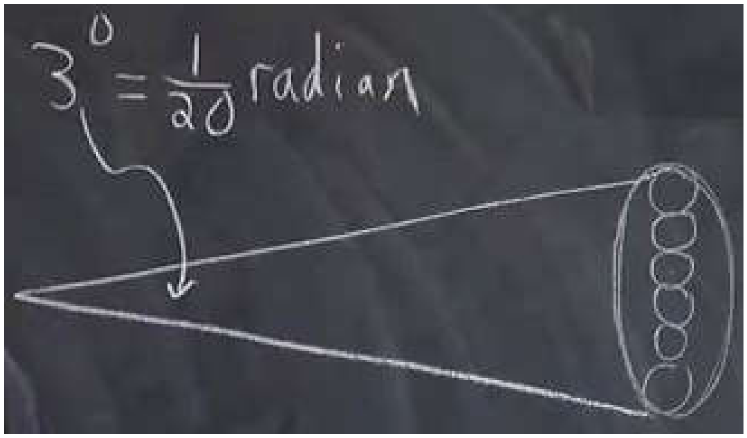


These objects were Cephei-variable stars, which we have encountered before, and which have the unique feature that they all actually growing and shrinking over a period of several days. Moreover, the amount of time it takes for these stars to pulsate is directly related to their intrinsic luminosity, how bright they really are. Once we know an objects true brightness, it is a simple matter to use its apparent brightness to calculate its distance from us.

It was undoubtedly with a trembling hand that Hubble calculated the distance to M31, our nearest spiral galaxy neighbor. It was over 1,000,000 ly away. Just imagine; light that can travel over 7 times around the world in 1 s takes over a 1,000,000 y to reach us from M31. Thus, when you go out on a clear autumn night and find M31 in the constellation of Andromeda you are seeing that object as it actually was when the first human creatures began to walk the earth.

With the knowledge of the distance to far-flung astronomical bodies, a wonderful side benefit emerged. We were able to find the dimensions of an object from its angular size in the sky. We did this recently when we discussed Cass-A, but here we'll calculate the size of M31. Modern, more accurate measurements place it about 2,000,000 ly away, and its apparent size in the sky is 3°, about the same apparent diameter as six full moons placed side by side.

1.1 What Is The Size Of The Andromeda galaxy?



Therefore, we have a big skinny triangle. The angle of opening is 3°, which is equal to about $^1/_{20}$ of a radian. We have to get everything in units or non-units of radian so that we can make the comparison of the size in the sky and distances together. We know we have six full moons spanning M31, and if the distance to M31 is 2,000,000 ly, then this distance here, the size of Andromeda actually is going to be:

$$\frac{2 * 10^6\, ly}{20}$$

Alternatively, approximately 100,000 ly across. With this awesome revelation about the size of the universe, and some of its constituents and avalanche of observations opened our eyes to yet more astounding facts. With this study of other galaxies and its exceedingly interesting relationship emerged. The further a galaxy was away from us, measured by the saphead variables and other techniques, the faster it appeared to be moving, as measured from the Doppler shift of its spectral features. It was as if the entire universe was somehow exploding into space. The faster each piece was moving, the further it would be away from anywhere else after a given amount of time. Because of this unique relationship between velocity and distance, known as the Hubble law in honor of its discoverer, we now had a new method for measuring distances to really remote objects. All we need to do is measure the Doppler red shift from the energy spectrum, and deduce the distance from a very simply equation.

$$\begin{aligned} v &= Hr \\ v &= \text{velocity} \\ H &= \text{Hubble constant} \\ &= 70 \, {}^{km/s}/_{Mpc} \\ r &= \text{distance} \end{aligned}$$

Equation 11 : Velocity of a very far astronomical object

Thus for each Mpc in distance away from us, which is about 3,000,000 y, the object's velocity increases by 70 $^{km}/_{s}$. For example, an object whose spectrum exhibits a velocity of 500 $^{km}/_{s}$, would be at a distance of about 7 Mpc from us. The stage was now set for the discovery of the quasars.

After World War II radio astronomy surged to the forefront of the astronomical frontier. Vast numbers of radio sources were discovered in the sky, which added greatly to our understanding of the processes that go on in our universe. However, one of the problems with early radio astronomy was, that because of the wavelength of the observed radio-light was so long, the positions of the sources were exceedingly hard to pinpoint. Therefore, it was very difficult to correlate the newly discovered radio emissions with known optical counterparts in the sky. However, by 1960, many positions were able to be refined, and we began to see what these cosmic objects were doing in the optical as well as the radio regime.

One of the techniques used to identify some of the sources involved looking at lunar occultation's. If a radio source just happened by chance to be along the path of the moon's orbit, the moon would pass in front of the object, thereby shutting of temporarily the earth bound radiation. By precise timing of the disappearance and reappearance of the source, accurate positions could be obtained.

Such sources located were 3C48 and 3C273. The 3C stands for the third 'Cambridge Catalogue of Radio Sources'. Cambridge University in England was a pioneer in the radio astronomy field, and the numbers after 3C were ordered by right ascension of the objects looked at. When Allan Sandage of Caltech saw the spectrum in visible light of 3C48, he said: "The thing was exceedingly weird!". Indeed, it was an object unlike any previously seen. Its optical appearance was extremely blue, and although it looked like a star, its spectrum was very strange indeed. None of the known elements appeared to be there. The well studied fingerprints of H, Ca, and other stellar constituents seem to be gone. Instead, other lines in the spectrum seemed to emerge at odd wavelengths corresponding to nothing we knew about in the laboratory. Then in 1963, the Dutch astronomer Maarten Schmidt realized that the patterns of lines in the spectrum of 3C273 were identifiable, but they corresponded to wavelengths red-shifted by an astounding amount. Never was a star like this seen before. Thus the objects, which now number in the thousands, were dubbed, quasi-stellar objects or QSO's or simple quasars for short.

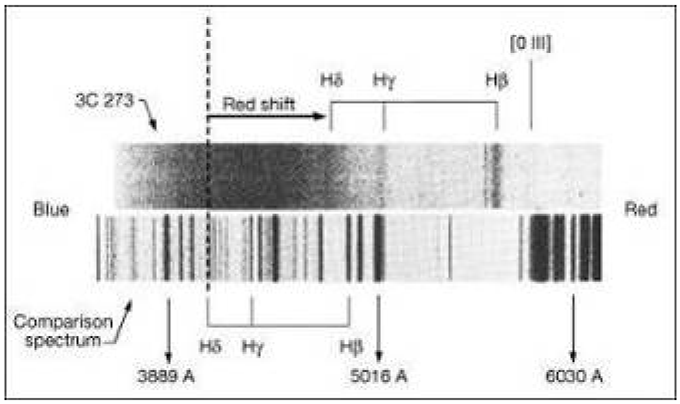


Illustration 52 : Optical spectrum of 3C273 compared to 'normal' spectrum

Let us look at the optical spectrum of 3C273. The three strong lines seen in the quasar spectrum are those of H, marked Hδ, Hγ, and Hβ. At rest on the Earth, they correspond to the following wavelengths.

$$H\beta = 486.1nm$$
$$H\chi = 434nm$$
$$H\delta = 410.2nm$$

Table 1 : Wavelength of common H-Lines

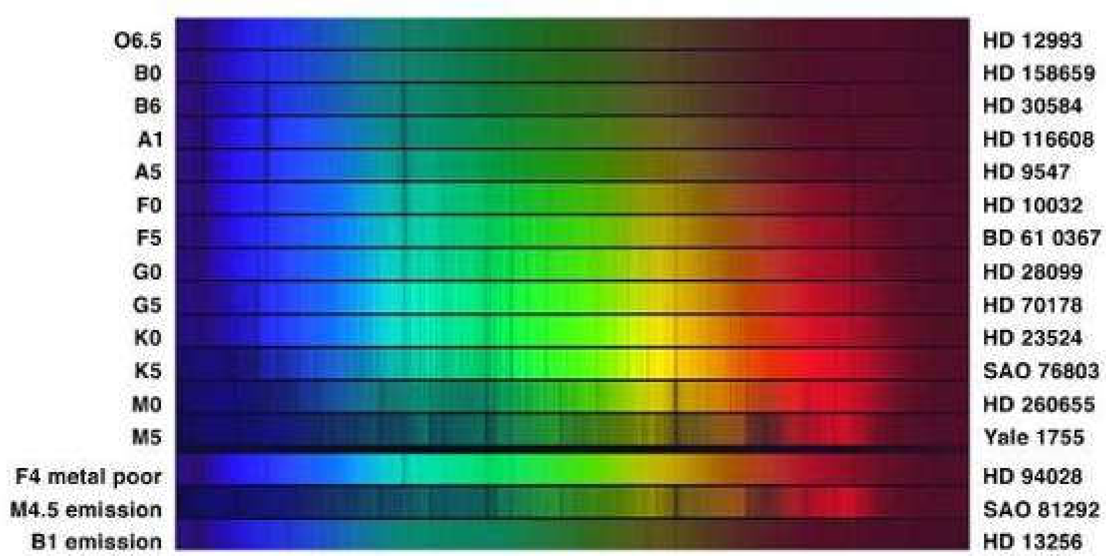


Illustration 53 : Stellar spectra of different Sun types

If you go back to the set of spectra we looked at when we studied stellar spectra, the A1 star has for its most prominent features exactly these lines. These lines and some others are identified in the comparison spectrum below the quasars. This comparison spectrum is taken in the observatory at rest, and represents what a mixture of gases looks like when nothing is moving with respect to the telescope. The *nm* stands for nanometers, and represents a unit of length equal to 10^{-9} m or 10^{-7} cm.

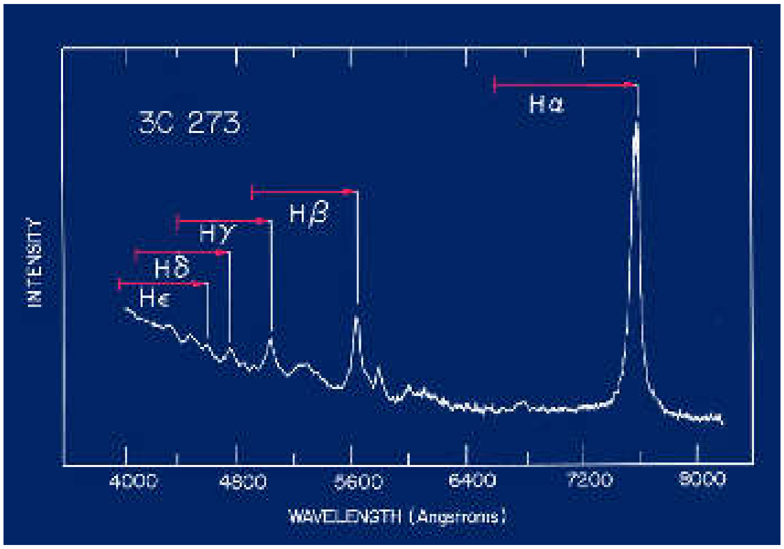


Illustration 54 : Intensity of H-lines in spectrum of 3C273

Here is another representation of the same spectra. Let us get the velocity and distance to 3C273. We will measure the relative positions of several lines in the comparison spectrum with an ordinary ruler. First, we need to figure out how many nm of wavelength on the spectrum corresponds to 1 mm on the paper. This is called the dispersion or scale of the spectra. Measure several pairs of lines, and take the average for a more accurate value. Note that the answers that we are talking and be given here will be different from your results, because of variations in printing of the page from computer to computer. For example, if the lines of Hβ and Hδ are separated by 36.5 mm in the comparison spectrum, the plate scale will be 2.08 $^{nm}/_{mm}$. Therefore, if we look at Hβ and Hδ, and they are separated by a distance equal to 36.5 mm, we can calculate, knowing what the wavelengths of Hβ and Hδ are, that the scale will be equal to 2.08 nm on the spectrum per mm on your piece of paper. Now we can choose one of the H-lines in the quasar spectrum, and see how far in mm it is from the corresponding rest wavelength. For example, if Hδ-line appears in the quasar spectrum at a distance of 33 mm to the right of the laboratory position, its wavelength-shift, $\Delta\lambda$, will be:

$$\Delta\lambda = 2.08\,{}^{nm}\!/_{mm} * 33mm$$

$$\approx 68.7nm$$

Now we can derive the velocity. If you remember, for our Doppler shift:

$$\frac{V}{c} \approx \frac{\Delta\lambda}{\lambda}$$

$$\approx \frac{68.7nm}{410nm}$$

$$\underline{V \approx 0.17c}$$

Remember, *V* is the velocity, *c* is the velocity of light, $\Delta\lambda$ is the amount in nm of the displacement of the line in the quasar spectrum, and λ is the wavelength in nm of the line at rest. See how close you can get to the correct red-shift of 0.158. Finally, now we can get the distance to the object.

$$V = Hr$$
$$H = 70 \,{}^{km}\!/_{s}\!/_{Mpc}$$
$$V = 5 * 10^{4} \,{}^{km}\!/_{s}$$
$$r \approx 700 Mpc$$
$$\underline{\approx 2.2 * 10^{9} ly}$$

Therefore, when you see this object through a telescope, you are viewing it the way it appeared 2,200,000,000 years ago, when only bacteria and algae were present on the Earth. Mammals were still 2,000,000,000 years away from existence on our planet. Thus these objects, though they look like stars, are so distant that they must be more luminous than the brightest galaxies. At over 2,000,000,000 ly and more, since 3C273 turns out to be the closest quasar, they are >1.000 times more distant than Andromeda, M31. Yet even at such gargantuan distances, many, including 3C273, are bright enough to be seen in small telescopes. To find out just how bright they really are, let us go to DS9, and check out 3C273.

At this point, please watch "Analyzing the Universe013.mp4"

Video 13 : Brightness of 2C273

Since this is the only strong source in the field a few of the satellite, we can say that this represents roughly the X-ray energy received from 3C273 in the energy band that CHANDRA is sensitive to. However, think for a moment. 3C273 is pouring out these photons everywhere in the sky. CHANDRA only picks up a very tiny percentage of them. The rest keep streaming out into space, where no X-ray satellite is there to see them. In fact, we can imagine a huge ball centered on 3C273 whose radius is equal to the distance from the source to the Earth. Each square centimeter of the tiny satellite's area must be multiplied by the area of the ball, which is $4\pi d^2$, where *d* is the distance from 3C273 to the Earth, to get the amount of X-radiation that 3C273 is giving off into space.

If 10^{-11} $^{erg}/_{s}$ of energy crosses each cm^2 of surface area at the distance of the Earth to 3C273, what is the X-ray output of 3C273?

Let us return to the blackboard and find out.

Think for a moment, 3C273 is pouring out these photons everywhere in the sky. CHANDRA only picks up a very tiny percentage of them. The rest keep streaming out into space where no X-ray satellite is there to see them. In fact, we can imagine a huge ball, centered at 3C273, whose radius is equal to the distance from the source to the Earth. Each cm^2 of our satellite's area must be multiplied by $4\pi d^2$, where *d* is the distance from 3C273 to the Earth, to get the amount of X-radiation that 3C273 is giving off

Well, it is very easy. The X-ray luminosity must be the flux that we measure in the sky times $4\pi d^2$. If the flux the observed brightness is $10^{-11} \,{}^{erg}\!/_{cm^2}\!/_{s}$, and our distance *d* of $2.2 * 10^{27}$ cm, we get:

$$E = 10^{-11} * \left(2.2 * 10^{27} * 4\pi\right)^2$$
$$\underline{\underline{\approx 6 * 10^{44} \,{}^{erg}\!/_{s}}}$$

This is close to 1,000,000,000,000 times the entire energy output of our Sun, and 10 times the luminosity of our entire galaxy. Finding a mechanism to produce this much energy would be difficult under any circumstances, but the quasars present an even more difficult puzzle. These objects fluctuate in brightness, and because of this, they must be rather small. As in the side; note that this equation is nothing more than the inverse square law of a light, if instead of knowing the distance we know the true brightness of the object along with its apparent brightness, here expressed as the flux, we can use this to solve for the distance. This is what we do, for example, with a Cepheid-variable star.

1.2 How Big Is 3C273?

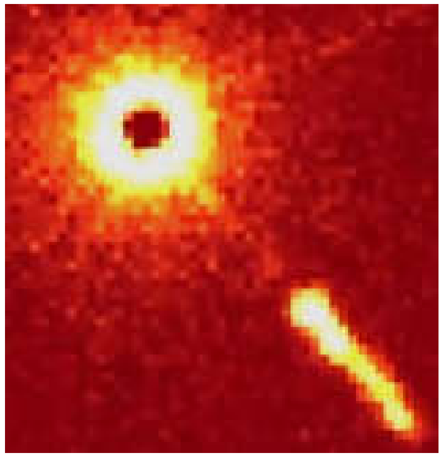


Illustration 55 : X-Ray Image of 3C273 with Jet

Note that the X-ray image of the round object is much smaller than that of CAS-A, but of course, that could be because of the stupendous distance to the quasar. In fact, the size of the object is consistent with a point source of light such as you might see when you look at an ordinary star that resides in our galaxy. However, we can certainly see the jet emanating from the side of the quasar, and measure its length.

At this point, please watch "Analyzing the Universe014.mp4"

Video 14 : Length of jet from 2C273

Along the diagonal, the jet is about 15 pixels long. Therefore, the angular extent in the sky has to be about 15 pixels times 0.5 $^{arcs}/_{pixel}$, which is the element of resolution for the CHANDRA satellite, times 1.4, because we are seeing those pixels, you know, kind of like as a diamond shape here, and we are measuring the distance across the diagonal instead of along the side. This works out to about 10 arcs. Therefore, the jet itself is 10 arcs in angular extent. Finally, we can figure out what the length of the jet is. It is just going to be:

$$L = \frac{10''}{206{,}265'' / _{rad}} * 700Mpc$$
$$= \underline{35.000pc}$$

This is bigger than the entire size of the Milky Way. In fact, recent observations using the CHANDRA satellite have shown a faint connection between the jet and the central part of the quasar, therefore, the jet is about twice this size.

By now, you are probably wondering; the main part of the quasar looks like a ball about 20 pixels across.

Does that NOT represent the size of 3C273?

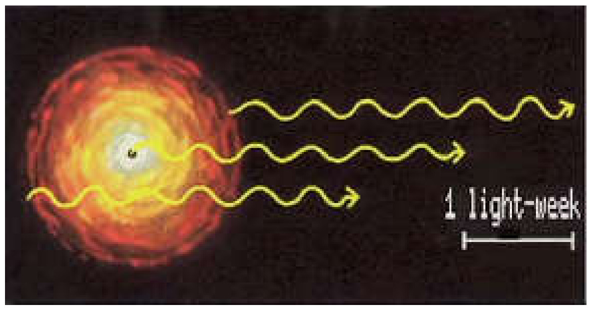
The answer is no. The reason is very similar to what happens when you take a photograph of a very bright light; the picture kind of spills over into adjacent regions on the film, or adjacent pixels on the digital detector. Since the jet is much fainter, it really does represent more accurately, a true size. In astronomical lingo, we say that the jet is resolved, because we can see details over its many pixels, but the main quasar is unresolved, since it is a featureless blob consistent with a point-like object that is very bright. It is exactly the same situation we have with stars in optical telescopes. All the stars, other than the Sun, are so far away as to be point-like in a telescope, although the brighter ones will appear to be bigger blobs on a pictures, because of the spillover effect. Therefore, we need another way to measure the size of the quasar. The answer comes from an unexpected place, the quasars time variations.

1.3 Quasar Time Variation

To see how this helps us, imagine a soccer field with you standing a few blocks away on the outside. When a team scores a goal a roar goes up from the crowd, all at once everybody is screaming. However, you do not hear the loudness immediately. The sound from the part of the stadium nearest you arrives first, followed by sounds from the more distant parts. It takes time for the sound to build up. In fact, if the velocity of sound is given as *c*, the amount of time it takes is:

$$t = \frac{L}{c}$$

The size of the stadium is *L*, and if all of the stuff, in this case sound, is traveling at speed *c,* it will take a time *t* for that sound to build up. Light is exactly analogous.



Here is a schematic of how an object of r = 1 lw might appear. Light from the side closest to the earth will arrive about two weeks earlier than the light from the point furthest away. Therefore, the light curve would appear to ramp up over a period of several weeks, even if the object changed its output all at once. Thus, by measuring how long it takes for the light coming from the quasars to change in intensity gives us an idea of how large the central engine is that is responsible for emitting the radiation.

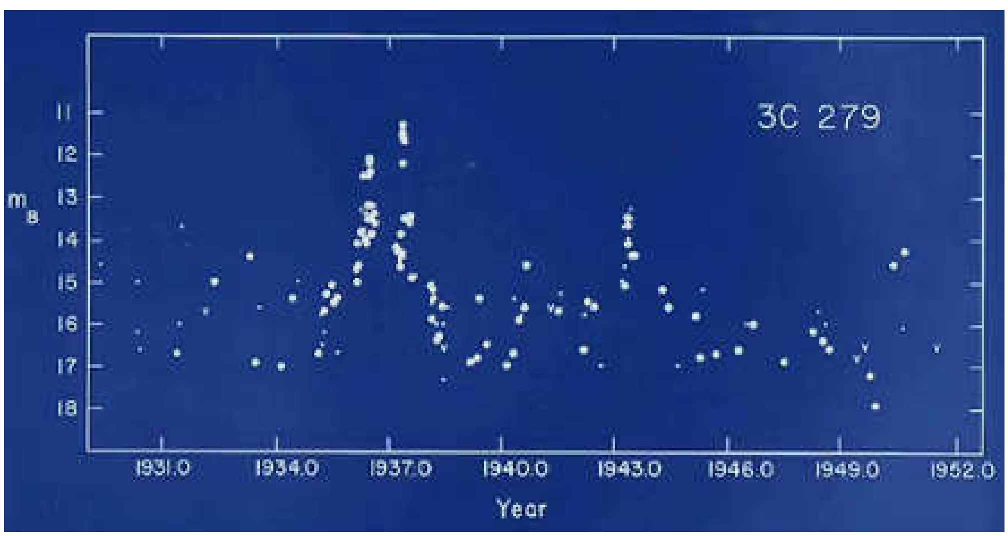


Illustration 56 : Optical variation of 3C279

Typical optical variations are shown here for the Quasar 3C279. These variations in 3C279 were discovered from a study of the Harvard survey plates, which are optical photographs, an established time variability on the order of months. Since then some quasars have exhibited variations on a scale of even minutes. Thus, the size of the central engine of these objects must be incredibly small, considering their stupendous output. If L = c^t, where now the *c* represents the velocity of light, we have objects that must be no larger than our Solar System in size, and yet their output is hundreds of times that of an entire galaxy.

1.4 Quasar Energy Transformation

Now 3C273 tends to be fairly constant in X-ray output. Therefore, we have no direct evidence for its size. However, in terms of investigating this class of objects it is clear we have our work cut out for us. We need to explain how they produce prodigious amounts of energy in a very small space.

What can possibly allow us to do this?

The most plausible explanation for these most implausible objects appears to be oddly enough similar to models that exist for binary X-ray stars in our own galaxy. The idea is that matter under the influence of an intense gravitational field loses energy, and releases enormous quantities of radiation in the process. Just as water goes over Niagara Falls losing its potential energy while providing us with power to drive electric generators. Therefore, material can fall into a stellar gravitational field, and emit light by colliding with neighboring atoms and heating up. Currently, the most popular model is that material near the quasar falls into a black hole.

Does a black hole swallow not everything around it?

This is a very common misconception, and the answer is no. Only material very close would inevitably be sucked into this type of object. In fact, if the Sun were suddenly to become a black hole, the orbit of the Earth would not change at all. However, other things surely would change, and in a hurry. How much energy is released, depends on the strength of the gravitational field, and how much mass is fed into the hole. The black hole really doesn't have a surface, but the material continues to yield energy to the outside world until it passes a place known as the Schwarzschild radius, named after a German astronomer who worked out its' properties nearly a century ago.

The Schwarzschild radius (R_S) is the distance from the center of a black hole at which the escape velocity will be equal to the speed of light.

Thus, lights trying to get out of a black hole will not be able to pass beyond that distance. It will look black, therefore. However, mass trying to get in from the outside will radiate like crazy, as it approaches the Schwarzschild radius, also known as the event horizon, and loses gravitational potential energy, similar to the way that water falling over Niagara Falls loses gravitational potential energy and drives electrical generators.

Although a correct analysis of this situation requires using general relativity. It turns out that the Newtonian analogue of this problem provides us with the correct answer. By using the principle of conservation of energy, and setting the escape velocity surrounding any mass *M* equal to that of light, we find that the Schwarzschild radius is given by a fantastically simple formula:

$$R_S = \frac{2GM}{c^2}$$

Equation 12 : Schwarzschild radius

That works out to $^{3\ \mathrm{km}}/_{\mathrm{solar\ mass}}$. Therefore, if you have an object equaling the mass of the Sun, its Schwarzschild radius would be 3 km. If you could squish the entire mass of the Sun into a volume of radius 3 km or less, you could make it a black hole. Notice; this is not the same thing as merely traveling 3 km from the center of the Sun, because the enclosed mass as that point is way less than one solar mass. For a black hole of mass 10^9 solar masses (1,000,000,000 solar masses) the size is approximately 10^9 km, which is approximately the size of our Solar System. Furthermore, the energy that a mass of *M* can lose, when it travels from infinity to the event horizon is given by, and here we will use the Newtonian expression for total potential energy from infinity:

$$E = \frac{GMm}{R_S}$$

Equation 13 : Gravitational potential energy

Therefore, now we can estimate the energy output of a black hole by determining the gravitational potential energy lost by a mass *m* as it travels the black hole of mass *M* and reaches Schwarzschild radius. Let us say, for example, that *m* is equal to one solar mass and our black hole is about 10^9 solar masses. The question is, if we have a mass equal to our own Sun, and it is gravitationally accelerated from far away to an R_S of where a 10^9 solar masses black hole exists.

In about 1 year, how much energy does the black hole emit under these circumstances?

$$E = \frac{\left(6.7 * 10^{-8}\right) * \left(2 * 10^{42}\right) * \left(2 * 10^{33}\right)}{3 * 10^{14}}$$

$$\approx 10^{54}\, ergs$$

Now, that is over 1 year. If you want, the energy released $/_s$, all we do is taking this quantity and dividing that by the number of seconds in 1 year.

$$E/_s = \frac{10^{54}\, ergs}{3 * 10^{7}\, s}$$

$$\approx 3 * 10^{46}\, ergs/_s$$

This is more than enough to power 3C273 as observed. Thus, our picture becomes this; an intense gravitational field provides the pull that sweeps material of mass, equal to our Sun each year into its confines. The energy released provides the X-rays, radio waves, and optical light that we see coming from the quasar. The variability is explained by the small size of the object. Even though it shines more brightly than hundreds of entire galaxies, it occupies a volume no larger than our Solar System. Neat, huh? In fact, it is hard to convey the excitement that the discovery of the quasars generated in the early 1960^s.

Martin Schmidt's picture even appeared on the cover of Time Magazine, but there was much skepticism regarding their true nature as well. Not only were the energy requirements enormous, if the quasars were really distant objects, but something else was observed in the 1970^s that made the whole puzzle even more unbelievable. It appeared as if 3C273 had yet one more trick up its sleeve. One that threatened to wreck our entire model.

What was it?

It seemed like some material in the jet was moving at many times the velocity of light, which violated, once again, all our ideas about the nature of space and time. Remember that we encountered a similar problem with GK Per.

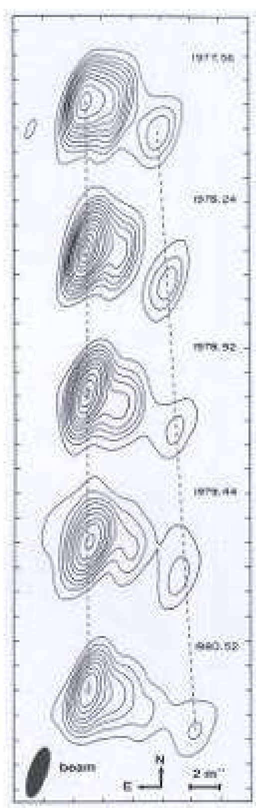
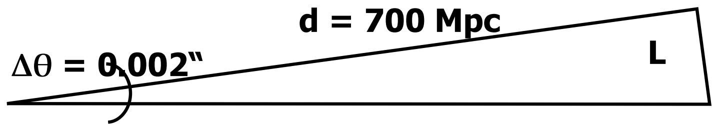


Illustration 57 : Radio Map of 3C273

Let us look at the radio map of 3C273, taken by researchers at the Owens Valley Radio Observatory and the National Radio Astronomy Observatory. Look at the little blob of material that is moving outward. It appears to change its position by .002 arcs in 3 y. Let us see what this seems to imply.



First, let us calculate how far it has moved across the sky in three years. Therefore, we are going to calculate the distance, *L*, and what we know is that the angle is .002 arcs. We also know that the distance is about 700 Mpc. Well, we know how to do all this stuff. We will divide $\Delta\theta$ by 206,265 to make the angle a radian measure, and we just convert our distance to ly by multiplying with 3.3.

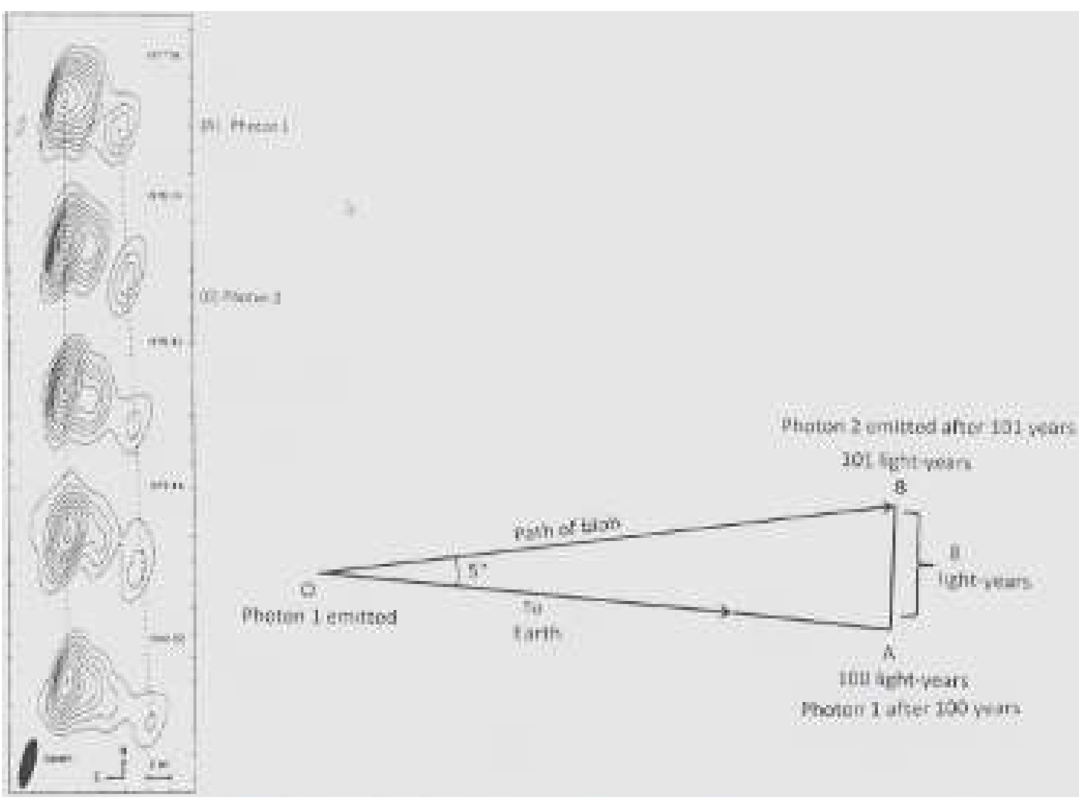
$$
\begin{aligned}
L &= \Delta\theta d \\
&= \frac{0.002 * 700 Mpc * 3.3}{206{,}265} \\
&= \left(10^{-8} rad\right) * \left(2.3 * 10^{9} ly\right) \\
&\approx \underline{\underline{23 ly}}
\end{aligned}
$$

Now what must its velocity be for this to be true?

If it moved 23 ly in 3 years, it was moving at v ≈ 8 $^{ly}/_{year}$, or about 8 times the velocity of light, since light travels 1 $^{ly}/_{year}$. Therefore, it looked like our velocity was 8 times the velocity of light.

How can this be?

Several models have been proposed, but the most likely idea is that the blob is moving not across our line of sight, but rather almost along it. However, this seems even more preposterous, because it would have to be moving even further to get to the position we observe now. However, the state of affairs is easily seen with the aid of the following diagram.



Let us imagine that the blob emits photon one that we see at the top of the radio map when it is at point *O*. The photon starts traveling the enormous journey in the straight line towards the Earth, and it reaches point *A* after 100 y. Thus, *A* is 100 ly from *O*. Meanwhile, the blob moving at almost, but not quite, the speed of light in the direction of *B*, gets to *B* after 101 y. At *B,* the blob emits a photon, photon 2, as it has been doing all along of course, towards the earth. The second photon also travels in a straight line towards the Earth. photon two's path is parallel to photon one's path, while the actually source, i.e. the blob, continues on its own path at the angle shown in this diagram. At this point, looking at triangle *OBA*, the blob appears to be 8 ly from *A*, but the photon emitted from the blob at *B* is actually only 1 year behind the original photon observed to be coming from *A*. Therefore, from the point of view of the Earth, the blob appears to emit light originally from the direction towards A, and once that light gets to us after billions of years, the light from *B* will be 1 year behind.

Our model is saved, but how does all these relate to our sense of cosmic history?

When the nature of the galaxies finally became known about 75 years ago, people were awed by the serene grandeur that these island universes presented. Stately in their motions, rotating once every 100,000,000 years, each containing up to 100,000,000,000 stars, they presented a picture of eternal tranquility. In fact, a popular cosmological model up to the 1960^s was the steady state theory, which posited an unchanging eternal infinite space where new and old objects stood side by side, uniformly spread throughout the far reaches of the universe. The discovery of the quasar sounded a death nail for this idea. Indeed, the implications of these observations were so bizarre, that many astronomers refused to believe the interpretation that we just presented, and instead sought to explain the red-shift, which implied vast distances, and hence stupendous energy output by other means. All these ideas failed, and rather reluctantly for, many scientist had to accept the picture we have painted here. When hundreds of other quasars were found, one fact stared us in the face. The nearest quasar remained ,3C273, is over 2,000,000,000 ly away from us.

Where were the more nearby ones? Why they were not distributed uniformly in space?

The answer seems clear. The quasars evolve in time. Remember that we see C273 as it was billions of years ago, because of its incredible distance. Thus, if a nearby quasar once existed, say in M31, we would be seeing it as it was a mere million or so years ago. However, suppose the quasar turns into a galaxy after a while. If quasars were a product of the early universe, only the most distant ones would still be visible, since we would be looking at them a time when they were active. Therefore, it is quite possible that if someone were to observe our Milky Way from a galaxy close to 3C273, they would see the celestial fingerprint of our galaxy as a quasar, since the light they will be observing from the Milky Way would be 2,000,000,000 years old. From their vantage point 3C273 would be a nearby, and probably a normal appearing galaxy.

Therefore, quite literally the quasars are important time machines, leading us back into the early history of the universe, which, as we have seen, seems quite different from the regions of space that we see today in our neighborhood. They portray a story of vast reservoirs of energy that seethe, in X-rays, optical, and radio waves, and they open our eyes to the cosmic history that is part of our common heritage.

2 To The Ends Of The Universe: The Cosmic Distance Scale – Part II

We have been on a long voyage through both space and time, which has taken us from our nearby bailiwick of the Milky Way, where most of our cosmic neighbors are merely hundreds to thousands of ly away. Out to the realm of the quasars and the early universe, where light has taken billions of years to reach us here on Earth. I want to conclude our discussions by giving you a short overview of our current ideas, concerning the history and ultimate fate of the universe as a whole. This is almost a presumptuous undertaking, but astonishingly, there is a lot we can say about this, which brings our conceptions of cosmology out of the dominion of myth, and into the province of probable scientific fact.

Of course, there is the caveat that we live, to borrow a quote from Loren Eiseley, in an unexpected universe, one that is continually full of surprises, and hence changes in our understanding. However, let us begin with some phenomena that we can comfortably assume, will not be altered drastically, at least qualitatively.

First, Hubble's discovery that the universe is expanding was the result of almost countless numbers of measurements of Doppler shifts of extra galactic objects, which almost unequivocally showed that the universe was expanding. Note that this is not just the galaxies are expanding away from us; everything is expanding away from everything else. It doesn't matter where in the universe you do these measurements. Indeed, it is much better to think about this, as if space itself is doing the expanding. Let us look at this carefully.

Imagine the universe as the surface of a balloon. On that balloon, we paste some rigid wire in the shape of galaxies in order to visualize this. The reason we use rigid wire is that we have objects that are held together by strong forces, that do not worry about the possible expansion of the balloon, which represents space itself in our toy model.

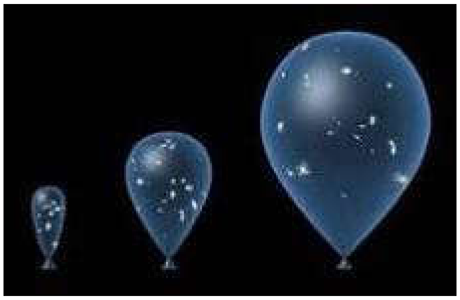


Illustration 58 : Toy model: Expanding Universe

Therefore, this is the picture. At one point early in the universe, our balloon is not very inflated, and we have some galaxies on it. Then it gets larger, and larger, and larger, as time goes on. You can see that if we are on or in the galaxy marked in red, everything seems to be expanding away from us.

However, does this mean that we are at the center of the universe?

Hardly. If we were in any location, for example, an other galaxy, this same thing would happen. Everything seems to be expanding away from us. Everything appears to move away from everything else. Let us see this more explicitly, using the following simple animation.

At this point, please watch "Analyzing the Universe015.mp4"

Video 15 : Expanding Universe

It is if the very fabric of space is expanding, and we are just going along for the ride. In fact, this has become what we call the cosmological principle. We are no longer at the center of the universe. Indeed, the universe has no center. Okay, so far, so good.

However, what about the shape of the universe? Why should it be in a spherical shape, like our balloon? Why not flat like a rubber sheet? Is there any way we can tell what is happening on that score?

It turns out, that the flatness of the universe is related to how much stuff is in it. A flat universe requires an exactly critical density of mass, and energy to maintain its shape.

How can we tell if this is the way things are?

One thing we can do is just try to cruise around it. I walk out and head to the ends of the universe. I keep going and going and well, maybe I'd better not do that. Suppose the universe is flat, and I just keep on going and going and going. I will never get back. At least, when I am on the surface of a balloon, I can just go around and around and come back eventually. It may take a couple a billion years. I will see some great things out there, and I will probably get some good exercise. Clearly, this will be impossible to do experimentally, especially if the universe turns out to be flat, and I never get back to finish this lesson.

Therefore, what else can we do, to try to determine the shape?

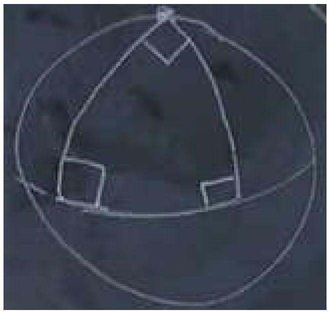


Illustration 59 : Spherical triangle on the Earth's surface

We can draw triangles.

What; draw triangles?

Well, we all know that the angles of a triangle sum to a 180°. Any triangle I draw, anywhere on this blackboard, the three angles, when I sum them together, will sum to 180°. However, we have made a crucial assumption. We have assumed that we are in flat space, the surface of our blackboard. Let us try that on a balloon, or the surface of the Earth. Therefore, we imagine that we have an Earth. In addition, here is the North Pole, and here is the Equator. We are just going to march down from the North Pole, until we hit the Equator. That is going to be a long way, but that is one side of our triangle. Then we are going to do a right turn. When we make that right turn, we are going to proceed along the Equator. Now, since we made a right turn, which is a right angle. We are going to proceed along the Equator, ¼ of the way around the circumference of the Earth. Then we are going to make another right turn, and keep on going back up to the North Pole. And you can see that we now, if we have gone a quarter of the way around the Earth, have made a triangle, it is a spherical triangle, but we can define a triangle, in terms of the shortest distance between two points, just like we defined a straight line on our blackboard. Low and behold, the angles are > 180°.

Huh, look at that. This is what happens if our universe is curved. I have an idea. Let us call our friends on M31, out there, a few million ly away, and on M87, out there, about 50,000,000 ly away! Okay, I am dialing. No answer? Still dialing? Oh, what a bummer!

Is there anything else we can do?

We can try to measure all this stuff in the observable part of the universe, and see how it stacks up with what we need for a flat universe. When we do that, we find we come up woefully short. There doesn't seem to be enough stuff in the universe to make it flat.

Well, case closed, right?

Uh-uh, it turns out we have real problems. We do have data on this, and it comes from the leftover radiation from the Big Bang itself. As the universe cooled, it left its cosmic imprint all over the sky, and we can actually see that leftover radiation from the Big Bang, using the WMAP-satellite.

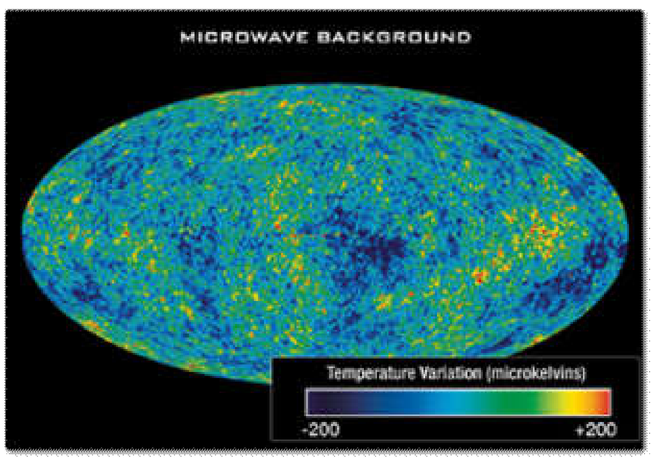


Illustration 60 : Microwave background scan from WMAP-Satellite

What we see here, is the first photograph ever possible of our universe. The black body radiation from when the universe was a mere 350,000 y old, streaming through space for over 13 billion y. The different colors represent tiny, tiny fluctuations in the temperature of the material at that time. The fluctuations are due to gravitational interactions that cause some over dense regions to be a little bit hotter than others. By examining carefully, the seeming jumble of different sized regions of differing temperatures, we have found out that the universe is indeed, very close to being flat.

Therefore, what is the matter?

We do not see it.

Where is the matter? What can it be? Are there clues anywhere else?

We can examine the rotation curves of stars going around the centers of their galaxies. When we do this, we find out something quite surprising. To understand this, we first return to our Solar System for a moment, and look at the planets as they go around the Sun. We all know about this now. We know that we have an acceleration that is given by:

$$\frac{v^2}{r} = \frac{GM}{r^2}$$

That is the centripetal acceleration, and that is a result of the inverse square law of gravity, where M is the mass of the parent object, the Sun, or whatever the object is going around. If we solve this for a circular speed, v, we see very clearly that the velocity is:

$$v \propto \frac{1}{\sqrt{r}}$$

There are some other numbers in there, but the crucial thing is that as r gets bigger, v gets smaller. Okay? Let us see how well $v \propto \frac{1}{\sqrt{r}}$ fits the Solar System?

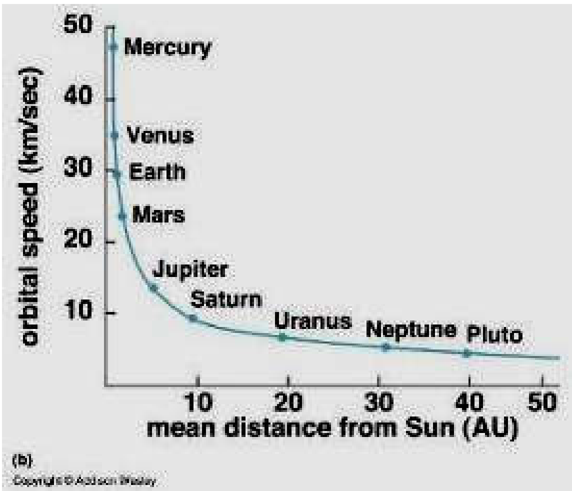


Illustration 61 : Orbital speeds in our Solar System

Look at that. The Sun's mass provides all the gravitational pull necessary to keep the planets in exquisitely precise agreement with Newton's law of gravity. However, look what happens when we look at orbits of stars around a galaxy?

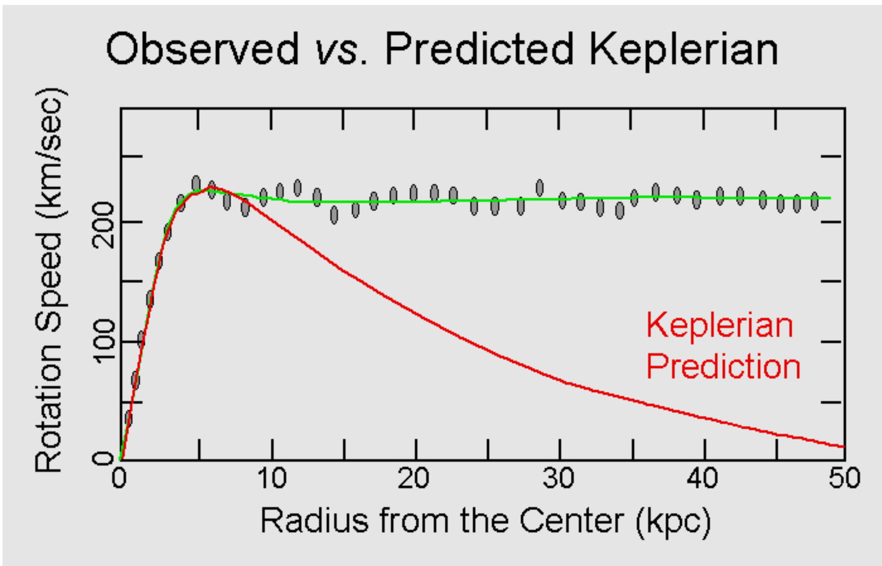
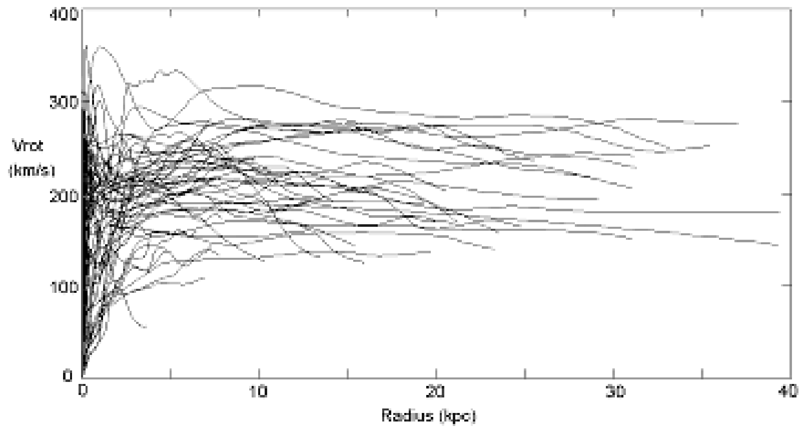


Illustration 62 : Rotation speed: Observed versus Keplerian prediction

It is way off. Even though, the center of the galaxy contains most of the visible mass, the predicted curve is not followed. Instead, the rotation curves stay flat, out to tremendous distances from the galaxy center. In addition, this doesn't happen only once. Look at these.



They are screaming at us. We are flat, we are flat, and we do not fall off.

What are you going to do about it?

Well, one thing we can do about it is say that there's just more stuff out there that we can't see; the famous dark matter. Just some strange stuff that doesn't interact, except gravitationally. Personally, I just feel these sounds too much like 'The emperor's new clothes', for my taste. I must confess, I am in the minority here in the astronomical community, but I feel that the problem is not with the inadequate amount of matter. The problem is, or to be fair might be, that we do not understand gravity at the very small accelerations, such as exists in the far reaches of the galaxies. It is not like we need just a pinch of the dark matter to do the trick. In the mid 1990^{s}, it was thought that fully 90 % of everything in the universe was mysteriously invisible. Therefore, here we have an obvious bone of contention in the astronomical community, but the most shocking thing was yet to come.

Whether or not you imagine a flat universe, a curved universe, or a universe filled with dark matter, one thing should be clear. Gravity ought to slow the expansion down (Remember our balloon expanding?). Well, if the galaxies are interacting, they should all be pulling on one another, trying to slow their expansion speed.

How could it be otherwise?

Therefore, we look deeper and deeper into space, measuring *v*, our velocity, via the Doppler Shift, and the distance *r*, from knowing the luminosity of various objects. In addition, the results are shown here.

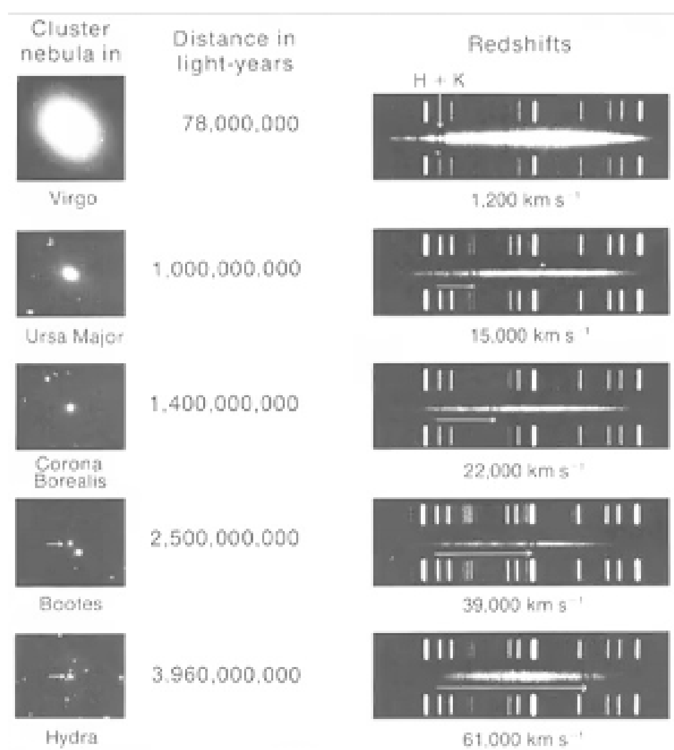


Illustration 63 : Velocity of Galaxies depending on their distance

The most distant galaxies, very faint and very tiny appearing, are moving the fastest; as expected. Then the incredible happened. By using type 1a Supernova, which, as we have seen, we have good reason to believe are standard candles, because they're all white dwarf stars of exactly the same mass, something didn't quite fit. After measuring hundreds of these objects in the far reaches of the observable universe, it became apparent that the universe was not slowing down, it was accelerating instead; absolutely astonishing.

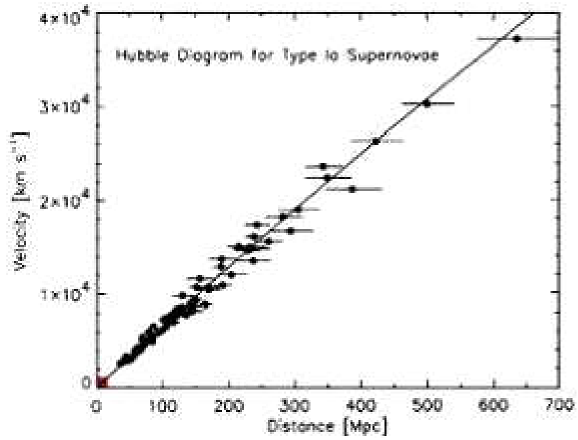


Illustration 64 : Hubble diagram for 1a supernova

The simple result is summarized here. No doubt about it. Things were further away than one would expect, if just a constant velocity were present.

What is going on here?

No one knows. The dark matter was lunatic enough, but now we need a source of dark energy, to explain this crazy acceleration.

What will be next? Will the universe eventually slow down and recollapse? Will it expand forever?

These are some of the unsolved questions that intrigue us. Therefore, these are exciting times in Astrophysics, with surprises galore. In just 10 y, the 90 % of the universe supposedly composed of dark matter has been reduced to about 25 %. In its place, over 70 % of the universe is now thought to be dark energy. The only thing that has remained more or less constant has been us, the ordinary stuff, the stuff of the stars, the stuff of the planets, relegated to a mere 4 % of the total mass energy content of the universe. We have to be content with our roles as observers and discoverers. Secure in the knowledge that even though we may be small and somewhat inconsequential, we can still behold the immensity and grandeur of the universe around us.

Additional Readings

1 Lenses/Optics, Scientific Notation/Dimensional Analysis And The Nature Of Light

1.1 Lenses/Optics

1.1.1 *Converging Geometric Optics: Convex Lens*

To focus images the majority of telescopes encountered in optical astronomy use convex lenses that work through refraction http://www.physics.rutgers.edu/analyze/wiki/lens_equation.html, or concave mirrors that reflect light. Contrary to popular belief, the main purpose of a telescope is NOT to magnify objects, but to collect a larger amount of light by using lenses/mirrors that have a much larger area than the human eye.

Besides its physical size, the focal length http://www.physics.rutgers.edu/analyze/wiki/lens_equation.html defines the critical property of a lens or mirror. We will discuss the importance of the focal length a bit later, but first let us look at the mathematical definition that directly affects how these lenses/mirrors are made. The focal length turns out to be:

$$f = \frac{1}{n-1} * \frac{r}{2}$$

Equation 14 : Focal Length

where n is the index of refraction of the lens glass, f is the focal length, and r is the radius of curvature of the lens, which is positive in the case of a convex lens (negative in the case of concave mirrors, which we will not cover in detail). This radius of curvature can be seen clearly below for a biconvex lens geometry (the 'bi' denotes the lenses are double-sided with the same curvature).

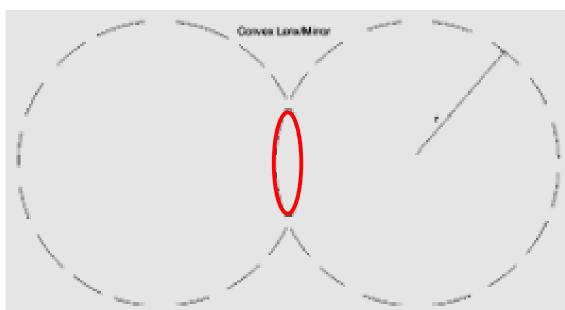


Illustration 65 : Biconvex lens/mirror

1.1.2 *Convex Lens: Ray Diagrams*

Now we define the common nomenclature used in geometrical optics. For the convex lens, seen in the image below, we see the parameters d_o, d_i, and f . All of these are lengths measured with respect to the lens/mirror, where d_o is the *object distance*, d_i is the *image distance*, and f is the *focal length*. The diagram below is known as a ray diagram http://www.physics.rutgers.edu/analyze/wiki/lens_equation.html, where the object is the physical item we wish to focus using a lens/mirror, and the image is the place where the light would yield a crisp replica of the actual object. A solid line runs through the center of lens/mirror and is the optical axis along the focal points lie. Note that the image appears inverted about the optical axis. Also, note that this particular ray diagram is only true while the object remains farther from the lens than the focal point.

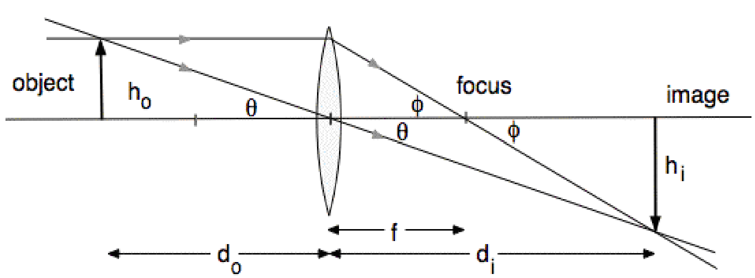


Illustration 66 : Ray diagram of a biconvex lens

Since we are now looking at ray diagrams, let us talk about the rules of how the rays work. We choose to show all rays leaving the head of the object (arrow seen above), although any other position on the object would work just as well.

1. Rays that leave the object parallel to the optical axis will pass through the focal point on the image side of the lens.
2. The ray that passes through the optical axis in the center of the lens continues undeviated by the lens.
3. A ray that passes from the object thought the focal point on the object side of the lens will be parallel to the optical axis as it leaves the lens to form an image (Vice versa to point 1).

1.1.3 A Mathematical Approach To The Convex Lens: Thin Lens Equation

Using our convex lens diagram we can construct a simple mathematical relationship between d_o, d_i, and f by looking at various similar triangles we can see in the diagram below.

We can see that the triangles $\Delta\{ABC\}$ (this denotes the triangle that has vertices at points *A*, *B*, and *C*) and $\Delta\{ADE\}$ must be similar, because they are both right triangles. The angle at point *C* in $\Delta\{ABC\}$ is the same as the angle at point *E* in $\Delta\{ADE\}$, since the lines |BC| (which denotes the line that runs from vertex *B* to vertex *C*) and |DE| are parallel. The line |AB| is equivalent to the object height, and the line |AD| is equivalent to the image height. Since we know that the triangles are similar, the ratios of corresponding sides must be equal. Therefore, we get

$$\frac{AB}{AD} = \frac{BC}{DE} \equiv \frac{h_o}{h_i} = \frac{d_o}{d_i}$$

Equation 15 : Magnification I

where h_o is the object height and h_i is the image height. Similarly, we can manipulate equation (2a) so that we have a definition for the magnification of the lens, and is defined as,

$$magnification \equiv \frac{h_i}{h_o} = \frac{d_i}{d_o}$$

Equation 16 : Magnification II

Note that the magnification is *not* a property of the lens by itself, but is instead a function of how far the object is placed from the lens.

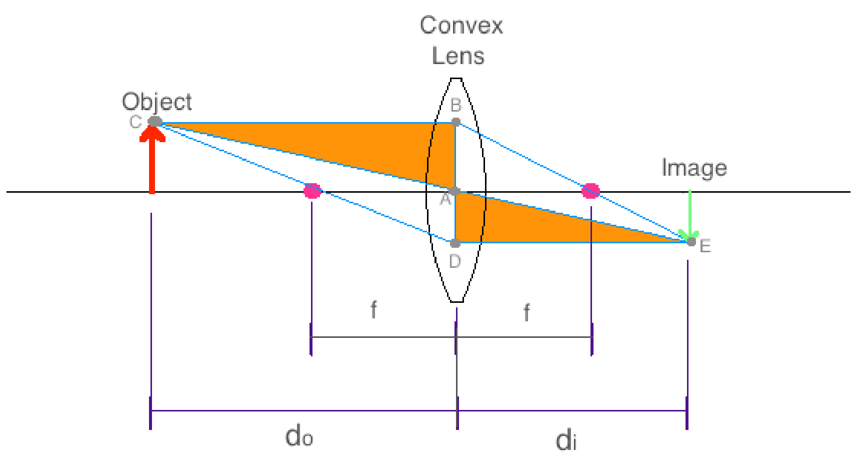
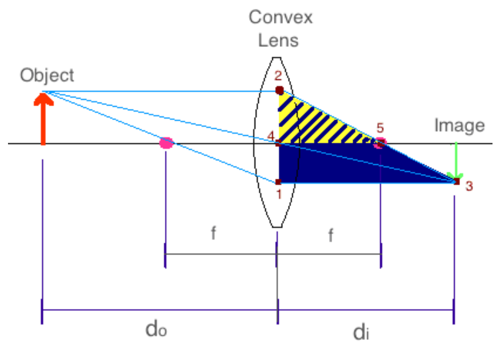


Illustration 67 : Magnification

Now let us create another pair of similar triangles in the image below. We can see that triangles $\Delta\{123\}$ and $\Delta\{425\}$ are similar triangles since the angle at point 2 for both triangles are clearly the same, while lines |13| and |45| are again parallel. The line |42| is equivalent to the object height and the line |12| is the sum of the object height and image height. Now we get the relationship:

$$\frac{|13|}{|45|}=\frac{|12|}{|42|}=\frac{d_i}{f}=\frac{h_i+h_o}{h_o}$$



Finally, we derive at the thin lens equation to be,

$$\frac{1}{f}=\frac{1}{d_o}+\frac{1}{d_i}$$

Equation 17 : Thin lens equation

The term $\frac{1}{f}$ is known as the optical power, and is generally given in units of diopters, which are simply inverse meters. These are the units optometrists use to prescribe corrective lenses or contacts (in addition to other key numbers, such as the distance between your pupils if you are getting eyeglasses).

1.2 Scientific Notation / Dimensional Analysis

1.2.1 Expression of Extreme Numbers: Scientific Notation

Throughout your time in the course, scientific notation will be extensively used. Therefore, it is crucial that you develop an understanding of this particular style of representing typically small or very large numbers, where adding trailing or leading zeros becomes cumbersome. Here is a great Scientific Notation Reference that you should all look into. For convenience, I am including a table of commonly used prefixes in science, typically in increments of powers of three.

Prefix	Scientific Notation	Shorthand Symbol	Example
atto-	$1*10^{-18}$	a	1 attometer
femto-	$1*10^{-15}$	f	1 femtometer
pico-	$1*10^{-12}$	p	1 picofarad
nano-	$1*10^{-9}$	n	1 nanosecond
micro	$1*10^{-6}$	µ	1 microgram
milli-	$1*10^{-3}$	m	1 milliohm
centi-	$1*10^{-2}$	c	1 centimeter
deci-	$1*10^{-1}$	d	1 deciliter
Base	$1*10^{0}$		1 Newton
Deca-	$1*10^{1}$	D	1 Decameter
Hect(o)	$1*10^{2}$	H	1 Hectoliter
kilo-	$1*10^{3}$	k	1 kilogram
Mega-	$1*10^{6}$		1 Megajoule
Giga-	$1*10^{9}$	G	1 Gigavolt
Tera-	$1*10^{12}$	T	1 Teraflop

Table 2 : Prefixes of scientific notation

1.2.1.1 Converting Physical Units: Dimensional Analysis

Besides gaining an understanding of scientific notation, you must become comfortable with the act of converting between different sets of units, which represent that same type of general physical meaning such as mass, length, temperature etc.. I have included another link to a Dimensional Analysis Walkthrough that you should all go through. In general, to convert units you are simply multiplying one physical value to another of the same type by multiplying by 1. This may seem a little misleading, but any definition for a unit conversion (i.e. 12 inches = 1 foot) can be re-expressed as unity if we simply divide both sides of the equation by one term appearing on either side of the equation (i.e. $\frac{12\ inches}{1\ foot} = 1$). Of course, when you do this though you must arrange the fraction so it will cancel the units you do not want, and leave behind the units in which you wish the physical quantity expressed.

As an example of dimensional analysis I turn to a humorous utterance made by grandpa (Abraham Jay-Jedediah 'Abe') Simpson on Matt Groening's 'The Simpsons' animated TV-program. In response to the metric system, Grandpa Simpson says, 'The metric system is a tool of the devil! My car gets 40 *rods* to the *hogshead* , and that is the way I like it.'

Therefore, our unit of measure that we are interested is a distance per unit volume of gas consumed. The unit we (in the USA and Great Britain anyway) all would know is $^{mi}/_{gal}$, or m.p.g., therefore, we will convert into these units from $^{rods}/_{hogshead}$.

1. We must find the relevant conversions between the units. Let us begin with length. 1 rod is the equivalent of 16.5 feet as defined in the English system of measure. We also know that there are 5,280 feet in 1 mile. We put this all together as follows:

$$1\ rod * \frac{16.5\ feet}{1\ rod} * \frac{1\ mile}{5.280\ feet}$$
$$= \underline{3.125\ miles}$$

This gives us our conversion between miles and rods yielding 320 rods in 1 mile (obtained by taking the reciprocal to the final answer the equation, and moving it to the other side).

2. Next, we must find a conversion for going between the units of volume measured in hogsheads to the more familiar gallon. Looking this up, we find that there are 63 US-gallons in 1 hogshead.

3. Now we put it all together as:

$$\frac{40\ rod}{1\ Hogshead} * \frac{16.5\ feet}{1\ rod} * \frac{1\ mile}{5.280\ feet} * \frac{1\ Hogshead}{63\ gallons}$$
$$= \frac{40\ rod}{1\ Hogshead} * \frac{1\ mile}{320\ rods} * \frac{1\ Hogshead}{63\ gallons}$$
$$= \underline{0.00198\ mpg}$$

Note the atrocious mileage Grandpa Simpson used to get...

Unit conversions can be tricky, but dimensional analysis is a powerful tool in solving these problems.

1.3 The Nature Of Light

1.3.1 Composition Of Light: The Electromagnetic Spectrum

Sir Isaac Newton discovered that the white light produced by the Sun separated into the colors of the rainbow when it passed through a prism. In order to demonstrate that it was not the prism itself distorting the light, Newton focused light of one particular color of the rainbow formed by a first prism into yet another prism, and the light that exited the prism was the same color of the light, which entered it.

As it turns out, the human eye sees but a narrow band of light in electromagnetic spectrum (depicted in the cartoon below with wavelength comparison to some length-scales of commonly known objects). Goddard Space Flight Center's education page on the Electromagnetic Spectrum does an exemplary job in breaking down the various regimes of light, and the devices we create to overcome the limitations of our own senses (you must really read this!).

The page also explains why we need space telescopes for various regimes in this electromagnetic spectrum. This relates especially to our class, since we are analyzing the universe in the X-ray regime, and, in particular, using the CHANDRA Space Observatory that currently orbits our earth 139,000 km (86,500 mi) above its surface (in comparison: the atmosphere has a thickness of roughly 100 km (62 mi)).

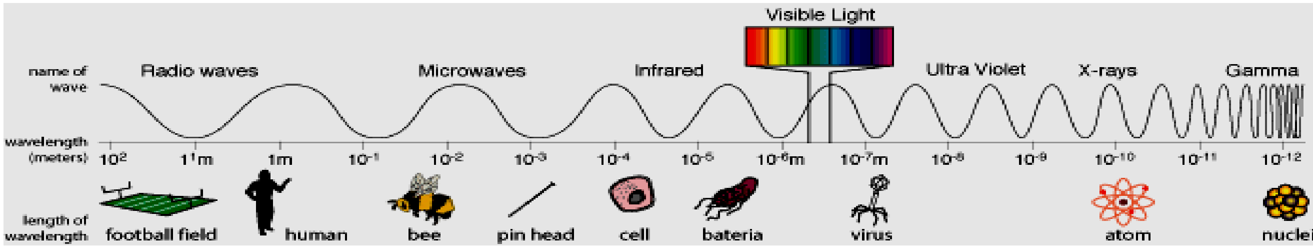


Illustration 68 : Spectrum of electromagnetic waves

1.3.2 A Universal Constant: The Speed Of Light

Throughout our universe, all photons appear to travel at a constant velocity in a given material. For a vacuum, James Clerk Maxwell showed that the speed of light, *c*, is about 300,000,000 $^{m}/_{s}$ (186,000 $^{mi}/_{s}$). This speed remains constant independent of the reference frame of the observer. This is counter-intuitive to our everyday experience though.

As a practical example, imagine we are driving our car at a speed of 60 $^{mi}/_{h}$ on the highway. Objects that are stationary on the ground will appear to be flying behind us at a speed of 60 $^{mi}/_{h}$. In addition, if we pass a car traveling in the same direction it will appear to move backwards in our frame of reference. Furthermore, if a car approaches us head-on at a speed of 60 $^{mi}/_{h}$, it will appear to fly by us at a speed of 120 $^{mi}/_{h}$. However, light is not like this at all! If you are approaching a photon near the speed of light, it will fly by you at the speed of light. In addition, if you are traveling very close to the speed of light, and shoot photons ahead of you, they will appear to leave the car once again at the speed of light. Albert Einstein spelled this entire out eloquently in his 'Theory of Special Relativity'. It turns out that the very nature of space and time itself is quite different than we ordinarily thought.

Earlier I stated that the speed of light for a given material remains constant. This implies then that the speed of light can take on different values in different media, and that is exactly what occurs. For example: the speed of light in fiber optic cables is approximately $^{2}/_{3}$ c. The ratio of the speed of light in a vacuum to the speed of light in a material *i* gives us the index of refraction of said material *i*. We commonly represent the index of refraction n_i as:

$$n_i = \frac{c}{c_i}$$

Equation 18 : Refractive index

Where c_i is the local speed of light in material *i*.

1.3.3 The Photon: A Particle And A Wave

Besides acting as a wave, a photon can also behave like a particle. This is best demonstrated by the photoelectric effect, where photons hit electrons in a material, and can cause them to be ejected if the individual photon has more energy then the binding energy of the electron that usually keeps them orbiting the nucleus in a stable fashion. Another demonstration that photons behave as discrete particles is the existence of atomic spectra that result from excitations of the electrons of an atom, which only occur at very specific (quantized) energies of photons.

On the other hand, the double-slit experiment is the classic experiment that shows how a photon behaves as though it were a wave, and is perhaps best described by the silky voice of Morgan Freeman in the video found here. Thus, light can be described as a discrete bundle or chunk (quantum) of energy, and as a wave with an unique wavelength or frequency.

The energy of a photon (γ) is defined as,

$$E_\gamma = h * \nu$$

Equation 19 : Energy of a photon I

where ν is the frequency of the photon, or the number of peaks in the wave pass a given point per second, and h is Planck's constant, which is roughly $7*10^{-34}$ Js. This (among other things) sets a limit for the minimum amount of energy any sub-atomic particle can have. A photon also exhibits an implicit relationship between its speed, wavelength, and frequency that goes as:

$$c = \lambda * \nu$$

Equation 20 : Photon; relation between speed, wavelength, and frequency

where c is the speed of light in a given medium, and λ is the wavelength of the light (the distance between peaks in the wave). We can then recast equation 19 in terms of wavelength instead of frequency of the light wave as:

$$E_\gamma = \frac{hc}{\lambda}$$

Equation 21 : Energy of a photon II

Note that Planck's constant h can be recast in different unit systems based on the desired energy units, for example eV, where now h = $4*10^{-15}$ eV. Moreover, we are free to use any unit of wavelength as long as the speed of light's length dimension is consistent. For instance; if you wanted to express wavelength in units of cm, you would need to define the speed of light to be, c = $3*10^{10}$ $^{cm}/_{s}$.

2 Astronomical Triangle, Atomic Spectra And The Cosmic Distance Scale

2.1 The Astronomical Triangle

2.1.1 Angular Size

In astronomy we are limited by the fact that we are looking at the sky as a 2D spherical shell in the sky with no immediate knowledge of the distance to an object, hence the true size or width across the sky of an astrophysical object in physical units of distance like km or ly is unknown. If we do have external information as to how wide an object is or how far away it is in physical units, we can use geometry to discover the unknown distance, physical size, or angular size of an astrophysical object.

The image below depicts the observer at the origin (0,0) of the figure below with a radius r that corresponds to the distance to some astrophysical object, and the angle θ is the angular size of said object. Let us now solve for the mathematical relationship, along with unit conversions, that show explicitly how an angular size translates to a physical size for some distance r away from the observer.

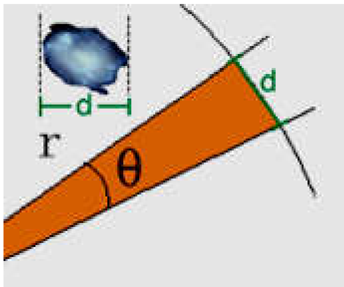


Illustration 69 : Translation of angular size to physical size

1. We know that the angular size of a distant object is rather small, and that it is some fraction of the circle explained above. The measure d represents the physical size of the astrophysical object of interest. Note that the length of the perimeter of the circle is called the circumference, and is defined as:

$$circumference = 2\pi r$$

Equation 22 : Circumference of a circle

2. In addition, since the angle is so small, the actual size of the galaxy, d, is essentially the same as the length of that portion of arc of the circle. Now we can set up a simple ratio, since the angular size of the galaxy is to 360 ° of the circle as the length d is to the circumference of the circle:

$$\frac{\theta[°]}{360[°]} = \frac{d}{2\pi r}$$
$$\frac{d}{r} = \frac{2\pi\theta[°]}{360[°]}$$

Equation 23 : Angular size to physical size

3. Typically, angular sizes are given in units of arcsec, therefore, we will convert θ into degrees from arcsec. Since there are 60 arcmin in 1°, and 60 arcsec in 1 arcmin, we can change the units of θ as follows:

$$\theta[°] = \theta[\text{arcsec}] * \frac{1[\text{arcmin}]}{60[\text{arcsec}]} * \frac{1[°]}{60[\text{arcmin}]}$$

Equation 24 : Conversion of arcsec to angle in degree

Now we can substitute both equations to get a much more compact and usable form that goes as:

$$\frac{d}{r} = \frac{2\pi\theta[\text{arcsec}]}{\frac{60[\text{arcsec}]}{1[\text{arcmin}]} * \frac{60[\text{arcmin}]}{1[°]} * 360[°]}$$
$$\cong \frac{\theta['']}{206{,}260['']}$$

Equation 25 : Substituted equation

Let us try an example where we know the physical size of a galaxy, but not its distance...

Illustration 70 : Galaxy and its diameter

We know that a galaxy of this particular type has a diameter of 200,000 ly. If we know the angular size of the galaxy on the sky is 5′, we can determine its distance from earth as follows:

With a little bit of algebra we can solve for r in the above equation, which is the distance to the galaxy. We find that the distance is:

$$r = \frac{d * 206{,}265['']}{\theta['']}$$
$$\cong \frac{200{,}00[ly] * 206{,}265['']}{5['']}$$
$$= \underline{8.25 * 10^9 ly}$$

Equation 26 : Example for distance calculation

We can rewrite our distance/angle equation in slightly more simple terms as follows:

$$r * \theta["] = 206{,}265["] * d$$

You can use this technique to measure distances or sizes as long as you know two of the three parameters.

2.1.2 Stellar Parallax

Measuring distances to astrophysical objects is, in general, a tricky business that depends greatly on the scale of the distance you wish to know. For stars that are close by, we can use a method known as stellar parallax. Stellar parallax is a method of measuring the distance to nearby stars by using straightforward geometry. If we wish to know the distance to a close star all we need to do (in theory) is observe it two times in one year separated by six months (Viewpoint A and Viewpoint B in the diagram below). Since we know the distance from the earth to the sun, our triangle has a base that is two times this distance. The angle ϕ is measured by looking at how the star of interest shifts in the sky when compared to stars at a much further distance, which appear to remain fixed (The reason the figure shows an angle of 2 ϕ is, because our convention is to assign ϕ to the angle subtended by the *radius* of the Earth's orbit around the Sun ('R' in the illustration) rather than the angle subtended by the *diameter* as indicated.). This technique is powerful, because it is a direct measure of distance to a star, but is limited by how well we can detect the apparent shift of a star against the background field of stars. This minimum detectable shift sets the furthest distance that can be measured using this technique, since as objects get farther away the apparent shift, ϕ, decreases.

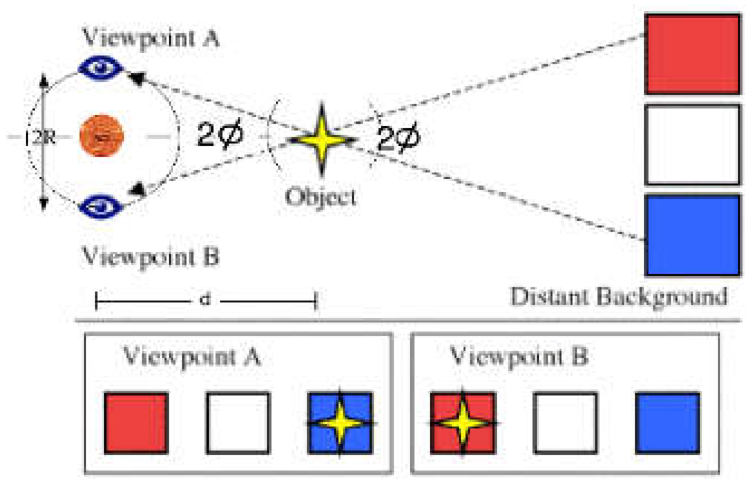


Illustration 71 : Stellar parallax

The equation for measuring these distances, *d*, is quite simple, and defines the unit of distance known as the ***parsec*** as follows:

$$d[\text{parsec}] = \frac{1}{\phi[\text{arcsec}]}$$

Equation 27 : Stellar parallax

Note that the angle ϕ must be in units of arcsec, not °, if we want to get the distance in ***parsec***, where:

$$\begin{aligned} 1\text{ parsec} &= 202{,}265\text{ Astronomical Units (AUs)} \\ &\approx 3.3\text{ light-years} \\ &\approx 3.1 * 10^{13}\text{ km} \\ &\approx 1.9 * 10^{13}\text{ miles} \end{aligned}$$

Equation 28 : Parsec conversion

Thus, 1 parsec is the distance that would be obtained by measuring a parallax of 1 arcsec, using a baseline of the Earth-Sun distance (which in turn defines 1 ***Astronomical Unit***). The total angular displacement for such an object over the 6-month span depicted above would be, naturally, 2 arcsec. Note: even the *nearest* star to us has a parallax of less than 1 arcsec.

2.2 Atomic Spectra

2.2.1 Fingerprints Of The Elements

As Dr. Matilsky discussed in his video lecture, atomic spectra occur due to the fact that orbital radii of electrons, and hence their energies, are quantized at specific levels determined by the atomic number (number of protons), and ionization state (number of electrons) in any given element. When looking at astrophysical objects we either see an absorption or emission spectrum. With absorption spectra, we see essentially continuum emission with certain wavelengths of light missing, and spectrographs usually render this as a black line.

Illustration 72 : Absorption spectrum

An emission spectrum, on the other hand, shows little or no continuum emission, and only displays light at specific wavelengths.

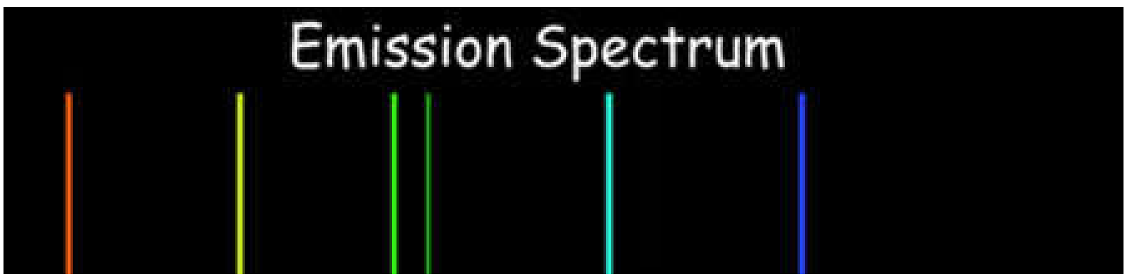


Illustration 73 : Emission spectrum

Whether an object will present an absorption or emission spectrum depends greatly on the geometry of the continuum source with respect to the observer on earth. Absorption spectra generally form when a continuum source, such as the central regions of a star, is directly in our line of sight, but behind our object of interest (which in this example), is the outer atmosphere of a star. Therefore, we receive most of the light from the continuum source, except for those wavelengths that can promote electrons in the outer atmosphere to higher energy levels, thus removing these photons from the game.

For emission spectra, the source of the continuum is oblique to the line of sight between the observer and the object. Therefore, the continuum source heats the object, and the electrons inside the atoms emit photons to move into lower energy states, which are always preferred by nature. We see examples of this in the so-called emission nebulae, which are regions of rarified gas that are heated by stars off to one side of the nebula.

Example Spectra: H-Like Atoms

H-like atoms are those atoms with only one electron remaining, regardless of the number of protons in the nucleus. An example would be singly ionized He, which is the lightest H-like atom, besides H.

Niels Bohr proposed a model of the atom that explained with startling accuracy, the appearance of the spectrum of H. In this model energy levels, E_n, of H-like atoms can be determined as:

$$E_n[eV] = \frac{Z^2 * (-13.6eV)}{n^2}$$

Equation 29 : H-Energy levels

Where Z is the number of protons in the atom, and n is the principle quantum number (just an integer!) that represents the quantized energy levels of the orbiting electrons. Also, note that the unit of energy is eV, or electron volts. These units are related to electric potentials measured in Volts, like your wall-socket is 120 V (if you are in the USA).

The energy of an emitted/absorbed photon is set by the difference in energy levels for a jump from one energy level with a given principle quantum number, n_{lower}, to another level with principle quantum number n_{upper}. The energies are negative, because our convention is to set the zero point of energy at infinity. An electron loses energy when it comes closer to the nucleus, (just as you lose potential energy when you roll down a mountain), and so its energy in the vicinity of the nucleus is negative. The reason it loses energy is because there is an attractive force between the -charged electron, and the +charged nucleus.

Example: Balmer Lines

In H the Balmer series is a special name given to transitions from larger *n* to the n = 2 state, or vice versa. For an example let us calculate the energy and wavelength emitted when the electron in an H-atom goes from n = 3 to n = 2 energy state.

1. First note that Z = 1, since there is only one proton in H. We can use the next equation to get the energies at the two different levels as:

$$\begin{aligned} E_2 &= \frac{1^2 * (-13.6eV)}{2^2} \\ &= -3.4eV \\ E_3 &= \frac{1^2 * (-13.6eV)}{3^2} \\ &= -1.51eV \end{aligned}$$

2. The energy of the photon is the difference of these two states,

$$\begin{aligned} E_{3\to2} &= E_3 - E_2 \\ &= 1.89eV \end{aligned}$$

The wavelength can be determined by the relationship:

$$\begin{aligned} E_\gamma &= h\nu_\gamma \\ &= \frac{hc}{\lambda_\nu} \end{aligned}$$

Where h is Planck's constant ($4.1*10^{-15}$ eV, and c is the speed of light (300,000 $^{km}/_{s}$). Rearranging we find that the wavelength λ is:

$$\begin{aligned} \lambda_{3\to2} &= \frac{hc}{E_{3\to2}} \\ &= \underline{656.5nm} \end{aligned}$$

This technique will work with any H-like atom. Just make sure you put Z in properly when you use the first equation. To make things simpler we can combine first and fourth equations, and generalize the observed wavelength of a photon that results from a transitions between two different quantum 'n' levels as:

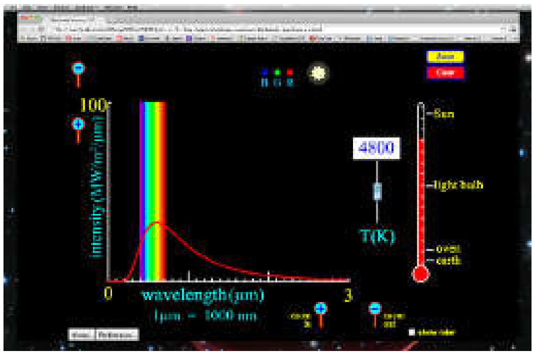
$$\lambda_{n_{upper}\to n_{lower}} = \frac{1}{0.011 * Z^2 * \left(\frac{1}{n_{upper}^2 - n_{lower}^2}\right)} [nm]$$

Note that the answer to the above equation is always a +value for the photon's wavelength. This is not only the wavelength for a photon emitted from transitioning from a higher to lower energy level, but is *also* the wavelength of a photon need to stimulate an electronic transition from a lower state to a higher one.

2.2.2 A Featureless Spectrum: Blackbody Radiation

Any object with a temperature greater than absolute zero will radiate energy away in the form of light. A blackbody spectrum is what would result if you had a perfectly black box that had a set temperature, and you observed the intensity of light at various photon energies. This is important, because we can often treat astrophysical objects, like stars, to be near-perfect blackbody emitters. Therefore, we can model the continuum emission upon which we see the absorption spectra. What this means is that, besides being able to observe the chemical make-up of a distant star, we can also determine its temperature near the surface.

Now for some hands-on experience! The University of Colorado's education department has developed a great tool, the Blackbody Spectrum Simulator. Click on the download button, and opening the downloaded file should open the applet in your browser as seen below.



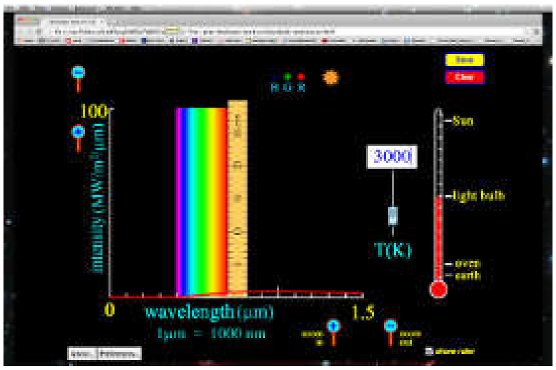
Let us discuss what we are seeing here in the plot. The x-axis represents the wavelength of light being emitted, and the y-axis represents the intensity, or strength, of emission of the blackbody radiation at a given wavelength. Note the units! Blackbody radiation is almost always given as energy per unit surface area of the object. There is a rainbow shown on the x-axis at the actual wavelengths of visible light.

You can change the temperature with the slide-bar just left of the thermometer on the right, or enter a temperature (in K) in the white box above the aforementioned slide-bar.

Now notice we can click the *show ruler* box at the bottom-right of the simulator. This brings up a ruler as shown in the figure below, which allows us to measure the height of the intensity at a given wavelength of light. Note that if you use the zoom in or zoom out buttons the scale of the ruler DOES NOT change. Therefore, if you wish to examine relative strength of a certain wavelength of light being radiated, you cannot zoom in or zoom out while doing this.

Exercise:

1. Click the zoom buttons until your x-axis runs from a minimum of 0 μm, to a maximum of 1.5 μm. Next, display the ruler, if it is not already, and move the left-edge of it to be on the 0.7 μm hash-mark, while placing the bottom of the ruler flush with the x-axis.



2. Enter a temperature of 3,000 K. Note the wavelength where the intensity is at its highest, and note the *height* of the emission at the 0.7 μm wavelength.

(You should find something like the maximum intensity occurs at a wavelength of about 1 μm, and the height of the emission is about 0.7 cm.)

3. Now repeat step 2 for temperatures of 4,500 K and 6,000 K.

Results: As we go through this, we see that as the temperature of the blackbody increases, the maximum intensity of radiated light takes on smaller wavelengths (greater energy). We also see that at any given wavelength the intensity of radiation emitted goes up as the temperature of the blackbody increases.

2.3 Cosmic Distance Scale

Understanding cosmological distances is easily out of the realm of our everyday intuition and experience, but we can appreciate scales of distances in various regimes. For scales solely in the astronomical regime, the NASA, HEASARC (The High Energy Astrophysics Science Archive Research Center) , put out a very nice applet for Interactive distance scale.

There is another ruler on htwins.net designed by Cary Huang that is a brilliant, Scale of Universe Interactive Ruler. This applet differs from the last in that it goes from the very smallest of scales to the largest of scales, which represent the two extremes where our current understanding of physics is more or less flushed out.

We encourage you all to play with these informative applets that will hopefully bring some context to your understanding of the cosmic distance scale! This section of the wiki is NOT introducing anything new to the ideas laid out by Professor Matilsky, but rather serves as a companion to help in understanding what was already presented.

3 Hertzsprung-Russell Diagrams, Stellar Evolution And Type Ia Supernova

3.1 Hertzsprung-Russell (HR) Diagrams

The astronomy department from the University of Nebraska-Lincoln hosts a great website with various educational resources, one of which is a very informative Interactive H-R Diagram. Let us take a closer look at this guide.

1. Open the Interactive HR-Diagram. Note that the red *x* appears initially at the position where the Sun resides.
2. Select *magnitude* for the y-axis. Note that this is *absolute magnitude*, which quantifies the brightness of a star by telling you how bright it would appear if it were placed at a distance of 10 parsec (32.6 ly) from an observer on Earth. This gives a true measure of the power output of a star.
3. Next select *show luminosity classes* under options, and leave the instability strip button unselected for now. Below these buttons are options for plotted stars. Select the *both the nearest and brightest stars* button so that your screen looks like mine below.

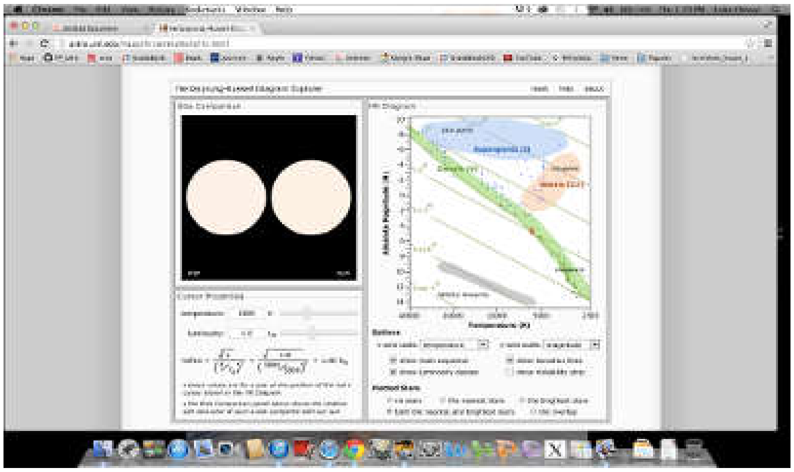


Illustration 74 : Screen-shot from 'Interactive H-R diagram'

4. Let us discuss some of the many features of the HR-diagram that are displayed. The x-axis of the plot represents the temperature of a star (please note that the temperatures go from high to low if we look from left to right on the axis). This temperature scale is in K, which is similar to the ° scale in that a difference of 1° C is equal to a difference of 1 K of temperature. However, zero (0) K is equal to about -273.15° C. 0 K is known as *absolute zero*, the temperature at which a gas would have zero energy, other than its own quantum fluctuations.

The green diagonal lines that run from top-left to bottom-right, are lines upon which stars have the same physical size (i.e. they represent lines of constant radius). If you look at the screen near the bottom left, you will see the mathematical expression that relates a star's temperature and luminosity (magnitude) to its radius. The green band that also runs from top-left to bottom-right with a thin red line running through it is known as the *main sequence*. These are stars in the prime of their life where they have achieved a stable balance between the gravitational force on the star that acts inward towards the fiery core, and the outward pressure changes resulting from the heat generated by fusion in the core. This balance is called **hydrostatic equilibrium**.

The top-right of the diagram is where the blue supergiants reside. The red giants are immediately down and to the right of the blue supergiants, while the white dwarf stars are shown as the gray band at the bottom of the H-R diagram. All of these groups are intimately related to the evolution of the main sequence stars, which are best described by two different paths that differ as a function of stellar mass.

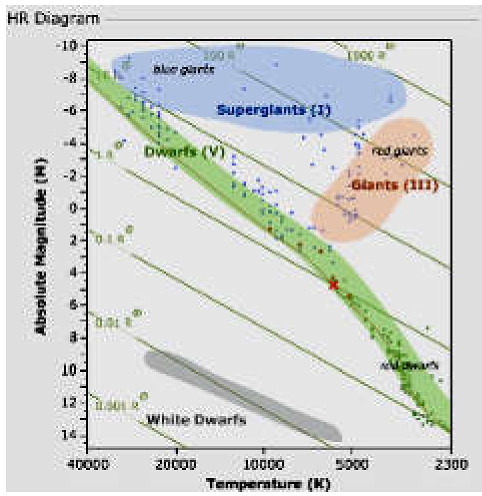


Illustration 75 : HR-diagram

3.2 Stellar Evolution

3.2.1 Low Mass Main Sequence Stars

$$M_{star} < 8 * M_{sun}$$

Equation 30 : Definition of 'Low mass main sequence stars'

Low mass stars, such as our own sun, spend the majority of their lifetime (billions of years) on the main sequence where they maintain hydrostatic equilibrium by transmuting H into He in their stellar cores through the process known as nuclear fusion. When all of the H is consumed, the gravitational force will compress the core further, raising it to a temperature high enough for it to begin fusing He, which temporarily prevents further collapse. The increased temperature also triggers a shell of H to begin fusing around the star's core in the aptly named process called H-shell burning. All of this increased radiation causes the star's envelope to expand outward into its new stage of evolution, the red giant phase.

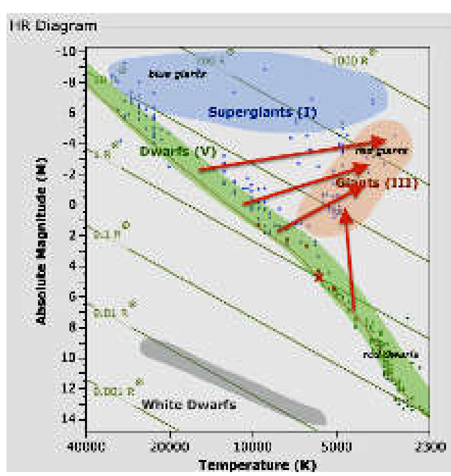


Illustration 76 : Evolution of 'Low mass main sequence stars' in a HR-diagram (1)

In the red giant phase and beyond the star will start a complicated set of fusion reactions, which changes the structure significantly. Eventually, when all its nuclear fuel is consumed, the core will lack the proper conditions to continue fusion burning. It is a highly complicated state of affairs, because stars of different masses will have different core temperatures, and hence differing abilities to burn each element in its interior. The mathematics, which govern these processes, are highly non-linear differential equations, and it is gratifying that the results that these equations yield match superbly the features of the HR-diagram.

Eventually, gravity will force the core of the star to contract, while the outer layers of the former star will puff out into a planetary nebula. The core of the star will collapse until quantum mechanical processes set in, which stabilizes the star once more. The Pauli exclusion principle, which states that two identical particles, electrons in this case, cannot have identical quantum mechanical properties (particle spin, energy, angular momentum, etc...), turns out to affect the structure of the star greatly. The pressure that results is called electron degeneracy pressure, and it stops the star from further collapse when its radius is about the same as the Earth. When the star reaches this new state, it is said to become a white dwarf. Without any further interaction, the white dwarf will exist indefinitely as it radiates away any residual thermal energy left over from its younger, more active days.

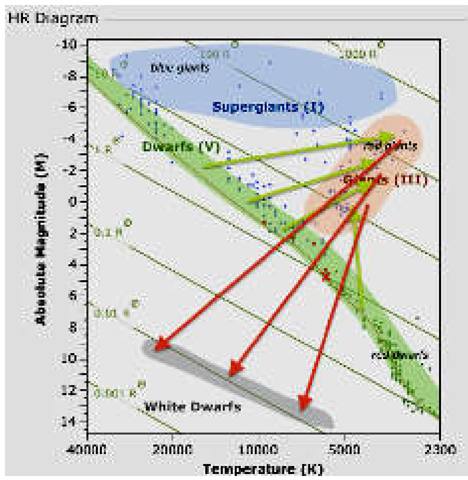


Illustration 77 : Evolution of 'Low mass main sequence stars' in a HR-diagram (2)

3.2.2 *High Mass Main Sequence Stars:*

$$M_{star} < 8 * M_{sun}$$

Equation 31 : Definition of 'High mass main sequence stars'

Stars with masses greater than about 8 times that our Sun shares some similarities with their low-mass counterparts, but also diverges greatly in the way that they evolve off the upper main sequence. Like low-mass stars, high-mass stars will consume all of their H in the core, and then begin fusing He while burning H in a thin shell around the He-core. This heating also causes the star to expand, but its luminosity and size now dwarf that of the red giants, putting them into another spectral type even more luminous called the red supergiants.

These stars will continue fusing successively heavier elements in their cores, but they can go beyond the ability to fuse C and O in their core, all the way up to Fe. Fe is the most tightly bound nucleus of all the elements, therefore, fusing elements beyond this actually requires an input of energy, instead of extracting energy that would normally prop the star up against its own gravity. At this point, the star's core will collapse beyond the point of a white dwarf, since the core has so much mass that even electron degeneracy pressure cannot halt the relentless onslaught of gravitation. The core collapses further until the electrons combine with the protons, and a super dense ball of neutrons remains that have approximately the size of New York City. Once again, the Pauli exclusion principle kicks in and prevents the neutrons from occupying the same quantum mechanical states, yielding what is known as neutron degeneracy pressure. There may be instances where gravity will be stronger than even neutron degeneracy pressure, and the core may collapse into a black hole.

At the time core collapse, something spectacularly violent occurs known as a supernova. These are among the most violent explosions in the universe, one in which the energy produced can be greater then the net sum of all the energy produced throughout the star's previous lifetime. Supernova seem like harbingers of death, but life as we know it today would be impossible without them. Stars can only fuse elements up to Fe in their fiery cores, but all of the heavier elements can be formed in supernova, as their temperatures are so high that even the heavy elements can be synthesized. As these massive stars explode, their entire contents are pushed outward enriching their galaxy with heavy elements that can now contribute to successive epochs of stellar and planetary formation.

3.2.3 Putting It All Together

Below is a great video from www.spacetelescope.org that will help your understanding of how stars evolve during their lifetime, using the HR-diagram as a visual aid. Note how all of the spectral classes of the HR-diagram are intimately related the evolution of stars off the main sequence. The time spent in the later phases of evolution of stars is almost negligible when compared to their lifetime on the main sequence, where they comfortably and leisurely fuse H into He.

HR-Diagram Animation

3.3 Type Ia Supernova

3.3.1 Atomic Spectra

Supernova are fundamentally classified by their atomic spectra into two groups: Type I and Type II. Examples of which are seen in optical light in the figure below (the x-axis of the plot is in angstroms (Å), which are defined as $1\ \text{Å} = 1.0{\times}10^{-10}$ m = 0.1 nm, while the y-axis is a measure of the brightness at various wavelengths observed with a spectrograph). The defining characteristic of a Type I supernova is a lack of H (vertical teal lines near maximum light as shown in the figure below at 6563 Å) in their spectra, whereas Type II supernova do show spectral lines of H. In the figure, the spectral signatures are seen as absorption lines (a dip in brightness from the continuum at a wavelength that corresponds to a specific electronic transition in a specific element). We believe that all of the Type II supernova result from the collapse of a massive star's core that leave behind a compact stellar remnant in the form of a neutron star or black hole.

We distinguish three subtypes of Type I supernova: Type Ia, Type Ib, and Type Ic. The spectra of a Type Ia supernova contain a distinct Si absorption line around 6,150 Å (vertical orange line as seen in the figure); this line is unique among Type I supernova, and, therefore, defines the subgroup a of the Type I supernova. Type Ib and Type Ic are characterized by the presence or absence of a He-line around 5,,876 Å (vertical purple). The light curves among the different Type I supernova are much more homogeneous than the light curves among Type II supernova.

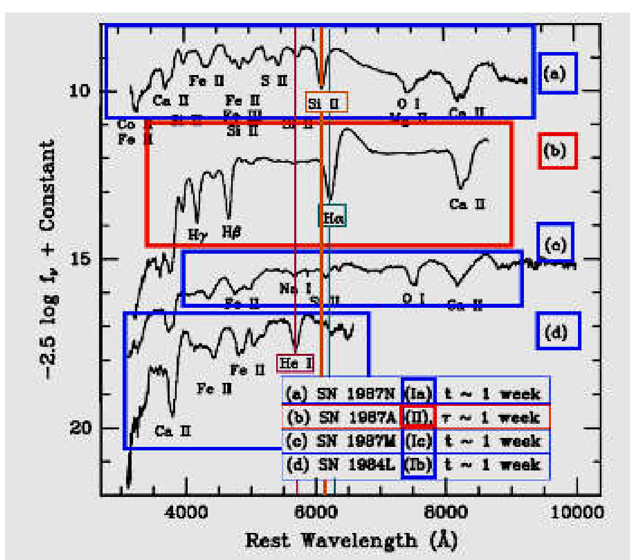


Illustration 78 : Atomic spectra of supernovas

Spectra of SN showing early-time distinctions between the four major types and subtypes. The parent galaxies and their redshift ($^{km}/_{s}$) are as follows SN 1987N (NGC 7606; 2171), SN 1987A (LMC; 291), SN 1987M (NGC 2715; 1339) and SN 1984L (NGC 991; 1532). In this review, the variables *t* and *τ* represent time after observed B-band maximum and time after core collapse, respectively. The ordinate units are essentially AB magnitudes as defined by Oke & Gunn (1983).

3.3.2 Light Curves

Another key piece of information astronomers use to classify supernova is their light curves. Unlike the light curve, you saw with GK-Per, a supernova light curve is not periodic since the explosion only occurs once. Light curves are used to subdivide the Type II supernova based upon how their brightness changes with time (e.g. Type IIp supernova are given the subgroup p, which stands for *plateau*. Since their light curves maintain a brightness close to that of their maximum brightness for a relatively long period of time, compared to others that fall off more rapidly after the time of maximum light). The figure below shows sample light curves from various types of supernova.

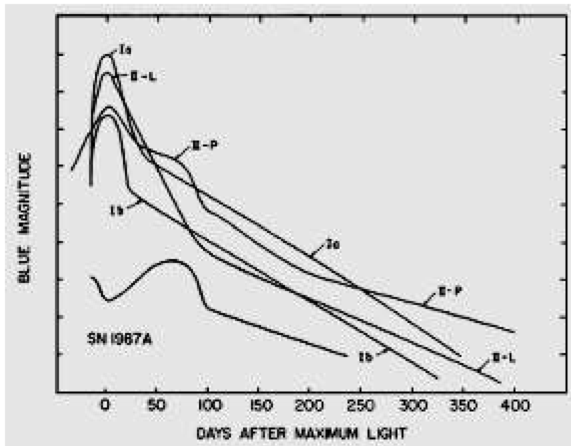


Illustration 79 : Schematic light curves for supernova

Supernova of Types Ia, Ib, II-l, II-p and SN 1987A. The curve for Ib includes Ic as well and represents an average. For II-l, 1979C and 1980K are used, but these might be unusually luminous.

Light curves and spectra from Type Ia supernova are remarkably homogeneous, especially when compared to the other types and subtypes of supernova. These homogeneities were the first indication that there seems to be a unique process or set of conditions that lead to Type Ia supernova. As it turns out, surprisingly perhaps, the likely culprit for these supernova is the lowly white dwarf. To understand why these stars best explain the homogeneities in Type Ia supernova, we must first look more closely at the conditions inside of a white dwarf.

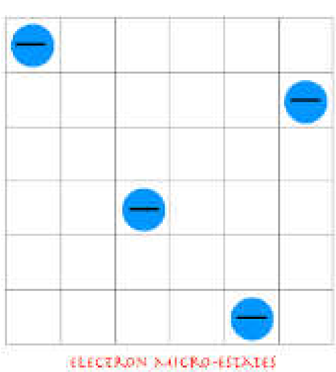
3.4 White Dwarfs: The Evolution Continues

We have discovered that the death of a massive star is not the only way to make a supernova. While it is true that most stars in our galaxy are about the same size as our Sun, and will end their lives enigmatically as burnt cinders, this does not necessarily spell the end of every low mass star's evolution.

As we noted before in section 3.2 of the course wiki a white dwarf is supported against gravity by electron degeneracy pressure. To understand electron degeneracy pressure in terms of the Pauli Exclusion Principle, let us consider a parable of overdevelopment in the recently built *micro-estates* gated community for electrons of evolved stars...

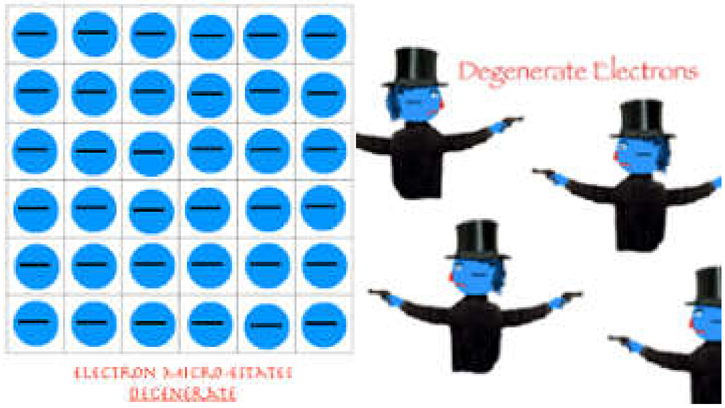
3.4.1 In The Beginning...

In the beginning the electrons didn't mind moving into the *micro-estates*, since it was at first spacious and quite posh. Electrons value their personal space above all else, therefore, the estates fit their needs perfectly. It was relatively easy for the electrons to keep well away from each other and maintain social norms.



3.4.2 After The Collapse…

After the great collapse of the core corporation, where millions of electrons were employees, conditions in the once envied *micro-estates* deteriorated. Electrons from all around were forced to move into the estates when their suburban lifestyle became untenable. Overcrowding began to run rampant, and the electrons degenerated into survival mode. Each electron was forced to hold the little ground he or she had left at any cost; forgotten were the days where electrons were bound by society to stay the customary distance away from one another.



In the story, this last piece of ground that an electron has is its *micro-estates*. In reality the analog to these are called microstates, and no two electrons, or any other fermion for that matter, can occupy the same state. A microstate is single discrete environment an electron can exist in, defined by several quantum mechanical properties (quantum numbers), and is a unique realization of an energy that a single electron can have. This fundamental property of electrons leads to an outward pressure that stops the star from collapsing further due to its own gravity. Under these conditions the force of repulsion that two electrons would normally experience (like charges repel!), and the thermal properties that usually determine pressure, are negligible compared to this degeneracy condition.

3.5 Explosion Mechanism

The maximum mass of a white dwarf is about 1.4 times that of our Sun, and is called the Chandrasekhar limit. Beyond this mass electron, degeneracy pressure would not be able to prevent the star from collapsing to a smaller size. Therefore, if the star could somehow acquire even more mass than 1.4 solar masses we could get further fireworks. Thus, an *isolated* white dwarf may continue to just placidly burn like a dying ember.

What will happen if, like a majority of stars in our galaxy, it is part of a binary system?

The possibility exists of an interaction between the white dwarf and its companion star which orbit each other in a stable gravitationally bound configuration (like the Earth and the Sun). In some situations, a white dwarf will be close enough to its companion star that matter will transfer from the companion onto the white dwarf in a process called accretion. As the white dwarf accretes more material from the companion its radius will shrink, and its mass will grow. This is where the Chandrasekhar limit comes into play, since it sets the maximum mass a white dwarf can have.

However, unlike the core of a massive star, which can have a variety of sizes, and hence a range of different explosions, a white dwarf will ignite as its mass approaches the Chandrasekhar limit, which is almost the same for all these objects. The once dying star will begin to undergo fusion again, but this time the star cannot expand, because it is bound as tightly as possible, and this newly kindled fusion creates more energy than that which holds the star together gravitationally. All of this leads to the violent explosion of the star in an event we humans have named a Type Ia supernova! (This author must admit though that the exact conditions for this spark that ignites the event is poorly understood, but a quite active and thriving field of study in astrophysics.)

3.6 Progenitor System: Unknown…

While the consensus view in astrophysics today is that Type Ia supernova result from a thermonuclear detonation of a C/O composite white dwarf that accreted mass from a companion, identifying the exact candidate for the companion star remains a point of contention. The two leading choices for this companion star are either an evolved main sequence star (single degenerate model), or a second white dwarf that coalesces with the previously mentioned C/O white dwarf (double degenerate model).

Current evidence suggests that the double degenerate picture is the most likely mechanism for Type Ia supernova. However, this does not rule out the possibility that Type Ia supernova can explode with the mechanism explained in the single degenerate model (at least some of the time anyway).

Cartoon: Single degenerate system

Image Credit: STFC/David Hardy

Cartoon: Merging double degenerate system

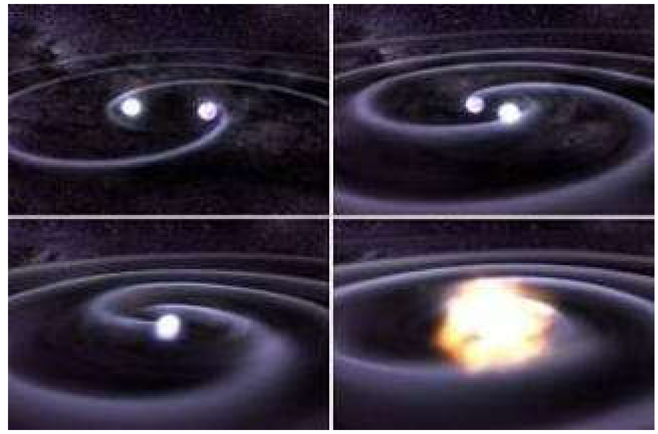


Image Credit: NASA/Tod Strohmayer (GSFC), Dana Berry (CHANDRA X-ray Observatory)

4 Neutron Stars And The Doppler Effect

4.1 Neutron Stars

4.1.1 Monsters Lurk In The Darkness

This week we explore Cen X-3, therefore, let us take a closer look at neutron stars. For this portion of the wiki, we will explore three well-written education pages on neutron stars and pulsars. This reading is **mandatory**, and you will be asked questions on the quiz relating to the material.

4.1.2 The Basics: Neutron Stars

The first site I would like you to visit is Professor M. Coleman Miller's page on the basics of neutron stars. You only need to read up to the ***What the @#$% makes Gamma-Ray bursts?*** part.

4.1.2.1 Introduction To Neutron Stars

Welcome to my neutron star page! I need to emphasize that the stuff I have here represents my opinions, and errors are not the fault of those patient pedagogues who tried to cram this information into my head. I will try to indicate when there is a dispute in the community, but I won't always be successful, therefore, do not use only this page to study for your candidacy exams! For those with serious interest in neutron stars and other compact objects an excellent reference is *Black Holes, White Dwarfs, and Neutron Stars* by Stuart Shapiro and Saul Teukolsky (1983, John Wiley and Sons).

For those who want a quick intro to selected cool things about neutron stars and black holes check out a poster I made for a science fair at the University of Chicago. If you'd like more detail about quasi-periodic oscillations in particular I wrote a pedagogical review based on my summer school lectures in Dubna, Russia, in August 2004. Here are the PDF documents.

I also have a link to some questions I have received about neutron stars and my answers. Here are the topics in this page:

The basics

Neutron star formation

Neutron star internal structure

Neutron star thermal and spin evolution

Isolated neutron stars (including pulsars)

Accreting neutron stars (e.g., X-ray bursters)

Classical μ-ray bursts

Soft μ-ray repeaters

4.1.3 Getting Started On Neutron Stars

Neutron Stars are the collapsed cores of some massive stars. They pack roughly the mass of our Sun into a region the size of a city. Here's a comparison with Chicago:

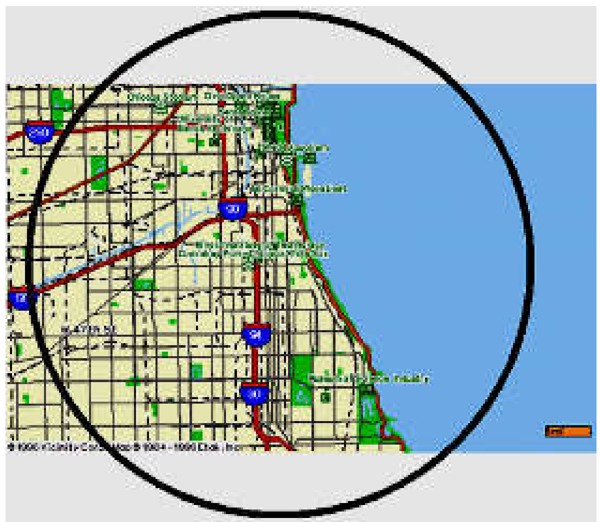


Illustration 80 : Neutron star vs. Chicago

$$\text{Mass} = 1.4\ M_{sun} \qquad \text{Radius}' = 10\text{ km}$$

$$\text{Spin rate} \qquad \text{up to } 38.000\text{ rpm}$$

$$\text{Density} \approx 10^{14}\ {}^{g}\!/\!{}_{cm^3} \qquad \text{Magnetic field} \approx 10^{12}\ \text{Gauss}$$

At these incredibly high densities, you could cram all of humanity into a volume the size of a sugar cube. Naturally, the people thus crammed wouldn't survive in their current form, and neither does the matter that forms the neutron star. This matter, which starts out in the original star as a normal, well-adjusted combination of electrons, protons and neutrons, finds its peace (aka a lower energy state) as almost all are neutrons in the neutron star. These stars also have the strongest magnetic fields in the known universe. The strongest inferred neutron star fields are nearly a hundred trillion times stronger than the Earth's field, and even the feeblest neutron star magnetic fields are a hundred million times Earth's, which is a hundred times stronger that any steady field we can generate in a laboratory. Neutron stars are extreme in many other ways, too.

Maybe you get a warm feeling when you contemplate high-temperature superconductors, with critical temperatures around 100 K?

Hah! The protons in the center of a neutron stars are believed to become superconducting at 100,000,000 K, therefore, these are the real high-T_c champs of the universe.

Overall, these extremes mean that the study of neutron stars affords us some unique glimpses into areas of physics that we could not study otherwise.

4.1.4 How Do We Get Neutron Stars?

Neutron stars are believed to form in supernova such as the one that formed the Crab Nebula (check out this cool X-ray image of the nebula from the CHANDRA X-ray observatory). The stars that eventually become neutron stars are thought to start out with about 8 to 20-30 time the mass of our Sun. These numbers are probably going to change as supernova simulations become more precise, but it appears that for initial masses « 8 solar masses the star becomes a white dwarf. For initial masses » 20-30 solar masses you get a black hole instead (this may have happened with supernova 1987A, although detection of neutrinos in the first few seconds of the supernova suggests that at least initially it was a neutron star). In any case, the basic idea is that when the central part of the star fuses its way to Fe, it can't go any farther, because at low pressures ^{56}Fe has the highest binding energy per nucleon of any element, so fusion or fission of ^{56}Fe requires an energy input. Thus, the Fe-core just accumulates until it gets to about 1.4 solar masses (the Chandrasekhar limit), at which point the electron degeneracy pressure that had been supporting it against gravity gives up the ghost and collapses inward.

At the very high pressures involved in this collapse, it is energetically favorable to combine protons and electrons to form neutrons and neutrinos. The neutrinos escape after scattering a bit, and helping the supernova happen. The neutrons settle down to become a neutron star, with neutron degeneracy managing to oppose gravity. Since the supernova rate is around 1 per 30 y, and because most supernova probably make neutron stars instead of black holes, in the 10 billion year lifetime of the galaxy there have probably been 10^8 - 10^9 neutron stars formed. One other way, maybe, of forming neutron stars is to have a white dwarf accrete enough mass to push over the Chandrasekhar limit, causing a collapse. This is speculative though, so I won't talk about it further.

4.1.5 The Guts Of A Neutron Star

We will talk about neutron star evolution in a bit, but let us say you take your run of the mill mature neutron star, which has recovered from its birth trauma.

What is its structure like?

First, the typical mass of a neutron star is about 1.4 solar masses, and the radius is probably about 10 km. By the way, the *mass* here is the gravitational mass (i.e., what you'd put into Kepler's laws for a satellite orbiting far away). This is distinct from the baryonic mass, which is what you'd get if you took every particle from a neutron star and weighed it on a distant scale. Because the gravitational redshift of a neutron star is so great, the gravitational mass is about 20 % lower than the baryonic mass.

Anyway, imagine starting at the surface of a neutron star and burrowing your way down. The surface gravity is about 10^{11} times Earth's, and the magnetic field is about 10^{12} Gauss, which is enough to completely mess up atomic structure: for example, the ground state binding energy of H rises to 160 eV in a 10^{12} Gauss field, versus 13.6 eV in no field. In the atmosphere and upper crust, you have lots of nuclei, so it isn't primarily neutrons yet. At the top of the crust the nuclei are mostly ^{56}Fe and lighter elements, but deeper down the pressure is high enough that the equilibrium atomic weights rise, so you might find Z=40, A=120 elements eventually. At densities of 10^6 g /cm3, the electrons become degenerated, meaning that electrical and thermal conductivities are huge, because the electrons can travel great distances before interacting.

Deeper yet, at a density around 4 * 10^{11} g/cm^3, you reach the *neutron drip* layer. At this layer, it becomes energetically favorable for neutrons to float out of the nuclei, and move freely around, therefore, the neutrons 'drip' out. Even further down you mainly have free neutrons, with a 5 - 10 % sprinkling of protons and electrons. As the density increases, you find what has been dubbed the 'pasta-antipasta' sequence. At relatively low (about 10^{12} g/cm^3) densities the nucleons are spread out like meatballs that are relatively far from each other. At higher densities, the nucleons merge to form spaghetti-like strands, and at even higher densities, the nucleons look like sheets (such as lasagna). Increasing the density further brings a reversal of the above sequence, where you mainly have nucleons, but the holes form (in order of increasing density) anti-lasagna, anti-spaghetti, and anti-meatballs (also called Swiss cheese).

When the density exceeds the nuclear density of 2.8 * 10^{14} g/cm^3 by a factor of two or three really exotic stuff might be able to form, like pion condensates, lambda hyperons, delta isobars, and quark-gluon plasmas. Here's a gorgeous illustration that shows the structure of a neutron star:

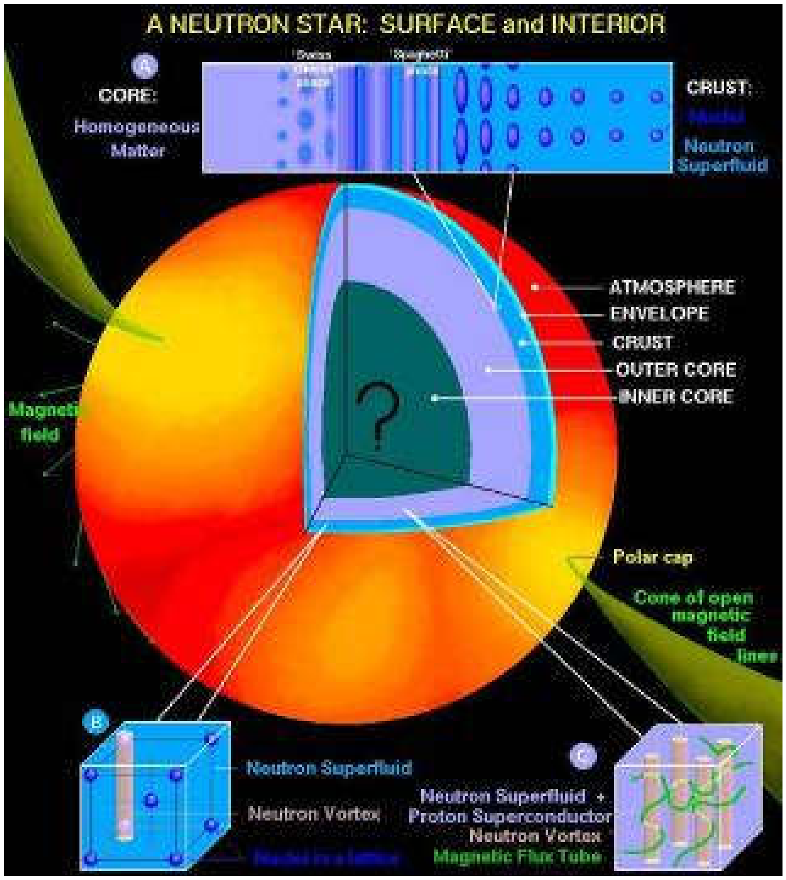


Illustration 81 : A neutron star: Surface and interior

Yes, you may say, that is all very well for keeping nuclear theorists employed.

However, how can we possibly tell if it works out in reality?

Unbelievably, these things may actually have an effect on the cooling history of the star and their spin behavior! That is part of the next section.

4.1.6 The Decline And Fall Of A Neutron Star

4.1.6.1 Thermal History

At the moment of a neutron star's birth, the nucleons that compose it have energies characteristic of free fall, which is to say about 100 $^{MeV}/_{nucleon}$. That translates to 10^{12} K or so. The star cools off very quickly, though by neutrino emission, therefore, that within a couple of seconds the temperature is below 10^{11} K and falling fast. In this early stage of a neutron star's life neutrinos are produced copiously, and since, if the neutrinos have energies < 10 MeV, they sail right through the neutron star without interacting; they act as a wonderful heat sink. Early on, the easiest way to produce neutrinos is via the so-called *URCA* processes:

$$n^{-} > p + e + (nu) \qquad \text{(nu) means an antineutrino}$$
$$p + e^{-} > n + nu$$

Equation 32 : URCA processes

If the core is composed of only *ordinary* matter (neutrons, protons and electrons), then when the temperature drops < 10^{9} K all particles are degenerated, and there are many more neutrons than protons or electrons that the *URCA* processes do not conserve momentum, therefore, a bystander particle is required, leading to the modified *URCA* processes:

$$n + n^{-} > n + p + e + (nu)$$
$$n + p + e^{-} > n + n + nu$$

Equation 33 : Modified URCA processes

The power lost from the neutron star to neutrinos due to the modified *URCA* processes goes like T^8; therefore, as the star cools down the emission in neutrinos drops sharply.

When the temperature has dropped far enough (probably between 10 and 10,000 y after the birth of the neutron star), processes less sensitive to the temperature take over. One example is standard thermal photon cooling, which has a power proportional to T^4. Another example is thermal *slowing-down radiation* in the crust, where an electron passes by a nucleus, and, instead of emitting a single photon as in standard *slowing-down radiation*, emits a neutrino-antineutrino pair. This has a power that goes like T^6, but its importance is uncertain. In any case, the qualitative picture of *standard cooling* that has emerged is that the star first cools by *URCA* processes, then by *modified URCA*, then by neutrino pair *slowing-down radiation*, then by thermal photon emission. In such a picture, a 1,000-y-old neutron star (like the Crab pulsar) would have a temperature of a few million K.

However, it may not be that simple. Near the center of a neutron star, depending on the equation of state, the density can get up to several times nuclear density. This is a regime that we can't explore on Earth, because the core temperatures of 10^9 K, that are probably typical of young neutron stars, are actually cold by nuclear standards, since in accelerators when high densities are produced it is always by smashing together particles with high Lorentz factors. Here the thermal energies of the particles are much less than their rest masses. Anyway, that leaves us with only theoretical predictions, which (as you might expect given the lack of data to guide us) vary a lot. Some people think that strange matter, pion condensates, lambda hyperons, delta isobars, or free quark matter might form under those conditions. It seems to be a general rule that, no matter what the weird stuff is, if you have exotic matter then neutrino cooling processes proportional to T^6 can exist, which would mean that the star would cool off much faster than you thought. It even appears possible in some equations of state that the proton and electron fraction in the core may be high enough that the *URCA* processes can operate, which would really cool things down in a hurry. Adding to the complication is that the neutrons probably form a superfluid (along with the protons forming a superconductor!), and depending on the critical temperature some of the cooling processes may get cut off.

So how do we test all this?

We expect that after 100 years or so the core will become isothermal (because it is then superfluid), and we can estimate thermal conductivities in the crust. Therefore, if we could measure the surface temperatures of many neutron stars, then we could estimate their core temperatures, which combined with age estimates and an assumption that all neutron stars are the same, would tell us about their thermal evolution, which in turn would give us a hint about whether we needed exotic matter.

Neutron stars are so small that even at the 10^6 K or higher temperatures, expected for young neutron stars, we can just barely detect them. Adding to the difficulty is that at those temperatures the peak emission is easily absorbed by the interstellar medium; therefore, we can only see the high-energy tail clearly. Nonetheless, ROSAT has detected persistent X-ray emission from several young, nearby neutron stars, therefore, now we have to interpret this emission and decide what it tells us about the star's temperature.

This isn't easy. The first complication is that the X-ray emission might not be thermal. Instead, it could be nonthermal emission from the magnetosphere. That could carry information of its own, but it makes temperature determinations difficult; basically, we have to say that, strictly, we only have upper limits on the thermal emission. Even if it were all thermal, we need to remember that we only see a section of the spectrum that is observable by an X-ray satellite, therefore, we could be fooling ourselves about the bolometric luminosity. In fact, some early simulations of radiation transfer through a neutron star atmosphere indicated that a neutron star of effective temperature T_{eff} would yield far more observed counts than a blackbody at T_{eff}. Thus, a blackbody fit would overestimate the true temperature. These simulations used opacities computed for zero magnetic fields. Thus, especially for low atomic number elements such as He, there weren't any opacity sources at 500 eV (where the detectors operate), therefore, in effect we would be seeing deeper into the atmosphere where it was hotter. Such simulations may be relevant for ms pulsars, which have magnetic fields in the 10^8 G to 10^{10} G range.

Most pulsars, though, have much stronger fields: on the order of 10^{12} G. In fields this strong the binding energies of atoms go up (as mentioned before, the ground state binding energy of H in 10^{12} G is 160 eV), meaning that the opacity at those higher energies rises as well. Thus, the X-ray detectors do not see as far down into the atmosphere, and the inferred temperature is less than in the nonmagnetic case. The details of the magnetic calculations are very difficult to do accurately, as they require precise computations of ionization equilibrium and polarized radiative transfer, and these are nasty in strong fields and dense, hot, matter. It seems, though, that when magnetic effects are included a blackbody isn't too bad an approximation. Stay tuned.

What does all this mean with respect to neutron star composition?

Yep, you guessed it, we do not have enough data. If you squint and look sideways at a graph of estimated temperature versus age, you might convince yourself that there is some evidence of rapid cooling, which wouldn't fit with the standard cooling scenario. However, unfortunately, the error bars are too large to be definite. We really need a large area detector that can pick up more stars. Features in the spectra would be nice too, but now that is just a dream. In the meantime, here is some recent data, plotted against several representative cooling curves that make various assumptions about the internal composition:

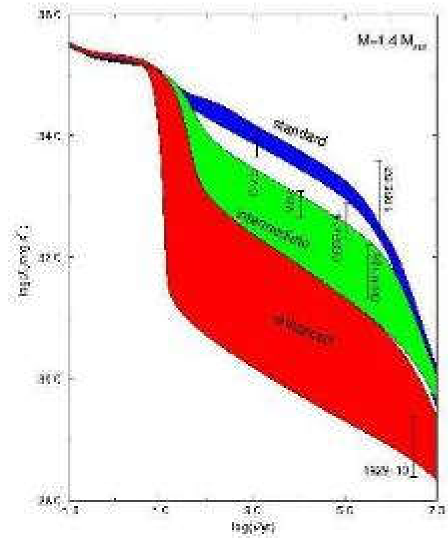


Illustration 82 : Cooling curves for neutron stars

4.1.6.2 Spin History

Neutron stars rotate very rapidly, up to 600 $/_s$.

However, how are they spinning when they are born?

They may be born rotating very fast, with periods comparable to a ms (although evidence is ambiguous). After that, they spin down ever after because of magnetic torques. This seems to be supported by the fact that some of the youngest pulsars, such as the Crab pulsar (33 ms) and the Vela pulsar (80 ms) have unusually short periods. After a pulsar is born, its magnetic field will exert a torque, and slow it down, with typical spindown rates of 10^{-13} $^{spin}/_s$ for a young pulsar like the Crab.

Although, overall the tendency is for isolated pulsars to slow down, they can undergo very brief periods of spinup. These events are called *glitches*, and they can momentarily change the period of a pulsar by up to a few parts in a million. The effects of *glitches* decay away in a few days, and then the pulsar resumes its normal spindown. In current models of *glitches,* the superfluid core and the normal crust are presumed to couple impulsively, and since the crust had been spun down by the magnetic field while the superfluid kept rotating at its original rate, this coupling would speed up the crust, leading to the observed spinup. It is very difficult to treat this process from first (nuclear) principles, because the critical angular velocity difference at which the crust and superfluid finally couple depends sensitively on various ill-determined properties of neutron superfluids, and since these properties are not directly accessible by experiments we may have to be satisfied by our current phenomenological description. Incidentally, the *glitch* should also heat up the crust, and late in the lifetime of the neutron star, heating by rotational dissipation can actually become a significant source of heat, and affect the temperature evolution.

Fine, that is an isolated neutron star. If the star has a companion, it can accrete from the companion, and have its rotational frequency altered that way. If the companion is a low-mass star, say ½ the mass of our Sun or lower, accretion tends to proceed by Roche lobe overflow (more on that later). This type of flow has a lot of angular momentum, therefore, the matter forms a disk around the star. The radius of the inner edge of the disk is determined by the strength of the magnetic field; the stronger the field, the farther out it can control the accretion flow (for a given accretion rate). The star then (more or less) tries to come to equilibrium with the Keplerian angular velocity of the matter at the inner edge of the accretion disk. This means that neutron stars with relatively small (10^8 - 10^9 G) magnetic fields can be spun up to high frequencies, and this is the accepted picture of how we get ms pulsars.

If the companion of the neutron star is a high-mass star (over 10 solar masses) instead, then the matter that makes it onto the neutron star goes in the form of a low angular momentum wind. Therefore, the neutron star isn't spun up to such high frequencies; in fact, some pulsars that are in high-mass systems have periods longer than 1000 s. The process of wind accretion is a very complicated one, and numerical simulations of the process push the limits of computers. It appears that, in some circumstances, a disk may form briefly around the neutron star, only to be dissipated and replaced by a disk going the other way. One barrier to understanding this kind of accretion is that, even with today's computers, high-resolution 3D-simulations just are not feasible now, therefore, we have to derive what insight we can from good 2D-calculations.

4.1.7 Misanthropic (Isolated) Neutron Stars

Neutrons were discovered in 1932, and very shortly afterward (in 1934) a suggestion was made by Walter Baade and Fritz Zwicky that neutron stars were formed in supernova. However, for many decades after that, neutron stars were just hypothetical phenomena that did not attract much interest. Since the stars are so small, people felt that the prospects for observing them were minimal, and thus little effort was expended on theory or observation of neutron stars.

This changed dramatically in 1967, due to serendipity and the diligence of an Irish graduate student by the name of Jocelyn Bell. Bell and her advisor, Anthony Hewish, were working on radio observations of quasars, which had been discovered in 1963. Bell and some other graduate students constructed a scintillation array for the observations, then she got down to examining the charts of data produced (she had to analyze the miles of charts by hand, since this was in the days before powerful computers!). One day she noticed a bit of *scruff* that appeared on the charts every second and a third. The scruff was so regular that she first thought it must be artificial. However, careful checking showed that indeed the signal was extraterrestrial, and in fact, that it must be from outside the Solar System. This source, CP 1919, was the first radio pulsar to be discovered.

The discovery initiated a storm of activity that has still not abated. A number of other pulsars were discovered, including one in the Crab Nebula, site of a famous supernova in the year 1054 that was observed by Chinese, Arabic and North American astronomers (but not recorded, as far as we know, by Europeans). Within a year or so of the initial discovery it became clear that:

1. Pulsars are fast, with periods known in 1968 from 0.033 seconds (the Crab pulsar) to about 2 sec.
2. The pulsations are very regular, with a typical rate of change of only 1 s per 10 million y.
3. Over time, the period of a pulsar always increased slightly.

With this data, it was realized quickly that pulsars had to be rotating neutron stars. With certain exceptions, that do not apply in this case, if a source varies over some time t, then its size must be less than the distance light can travel in that time, or ct (otherwise the variation would be happening faster than the speed of light). Thus, these objects had to be less than 300,000 $^{km}/_{s}$ * 0.033 s, or 10,000 km in size. This restricts us to white dwarfs, neutron stars, or black holes. You can get a periodic signal from such objects via pulsation, rotation, or a binary orbit. White dwarfs are large enough that their maximum pulsational, rotational, or orbital frequencies are more than one s; therefore, this is ruled out. Black holes do not have solid surfaces to which to attach a beacon, therefore, rotation or vibration of black holes is eliminated. Black holes or neutron stars in a binary could produce the required range of periods, but the binary would emit gravitational radiation, the stars would get closer together, and the period would decrease, not increase (and would do so very quickly, too!). Pulsations of neutron stars typically have periods of ms, not s. The only thing left are rotating neutron stars, and this fits all of the observations admirably. Here's an animated gif of a pulsar.

There have now been more than 1000 radio pulsars discovered, with periods from about 1.4 ms to > 5 s. Their discovery is considered one of the three most important astronomical discoveries in the latter half of the 20th century (along with quasars and the microwave background), and in part for his role in the discovery of pulsars Anthony Hewish shared the 1974 Nobel prize in physics.

4.1.8 Social (Accreting) Neutron Stars

Not all neutron stars are destined to lead a life of isolation. Some of them are born in binaries that survive the supernova explosion that created the neutron star, and in dense stellar regions, such as globular clusters, some neutron stars may be able to capture companions. In either case, mass may be transferred from the companion to the neutron star, as mentioned in the spin evolution section above.

If the companion star has less than the mass of our Sun, the mass transfer occurs via Roche lobe overflow. If part of the companion star's envelope is close enough to the neutron star, the neutron star's gravitational attraction on that part of the envelope is greater than the companion star's attraction, with the result that the gas in the envelope falls onto the neutron star. However, since the neutron star is tiny, astronomically speaking, the gas has too much angular momentum to fall on the star directly, and, therefore, orbits around the star in an accretion disk. Within the disk, magnetic or viscous forces operate to allow the gas in the disk to drift in slowly as it orbits, and to reach eventually the stellar surface. If the magnetic field at the neutron star's surface exceeds about 10^8 G, then before the gas gets to the stellar surface the field can couple strongly to the matter, and force it to flow along field lines to the magnetic poles. The friction of the gas with itself as it spirals in towards the neutron star heats the gas to millions of degrees, and causes it to emit X-rays. Some characteristic dimensions of this sort of system are displayed in the illustration.

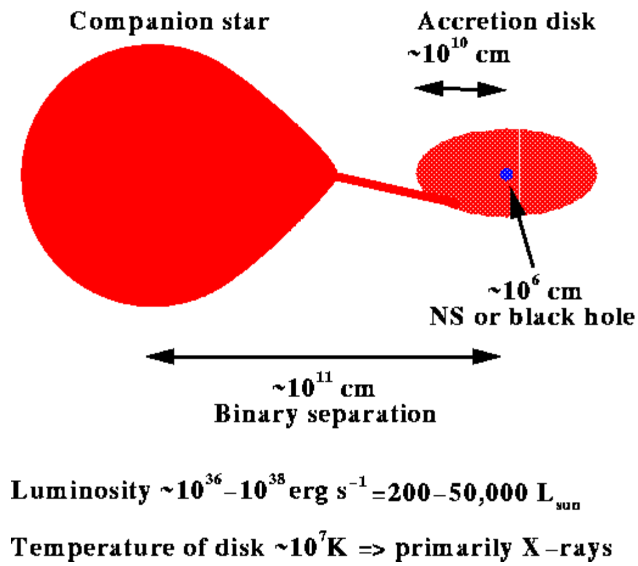


Illustration 83 : Accretion disk around neutron star or black hole

Here is an illustration of the inner region where the neutron star's magnetic field controls matter:

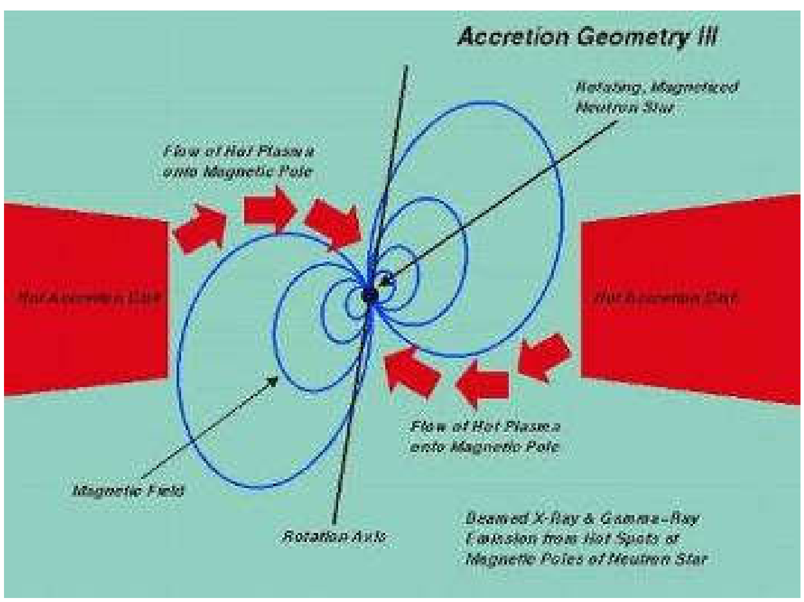


Illustration 84 : Neutron star's magnetic field controls matter

Neutron stars in these kind of systems are believed to have surface magnetic fields between 10^7 and 10^{10} G. This means that the accreting gas can spiral very close to the neutron star before it is grabbed by the magnetic field. At such a close distance, the orbital frequency is very high (hundreds of Hz), therefore, the neutron star is spun up rapidly. As mentioned earlier, this is how we think we get ms pulsars. Those ms pulsars, by the way, are extremely stable rotators; the best are at least as stable as atomic clocks! There have been suggestions that using ms pulsars as cosmic clocks could tell us about all sorts of exotic things, such as the presence of a background of gravitational radiation left over from the Big Bang.

Another fun phenomenon associated with neutron stars that have low-mass companions is X-ray bursts. These typically last a few seconds to a few minutes, and have a peak luminosity nearly a 100,000 times our Sun's luminosity. The model for these bursts is that as H and He is transferred to the neutron star from the companion, it builds up in a dense layer. Eventually, the H and He have been packed in a layer so dense and hot that thermonuclear fusion starts, which then converts most or all of the gas into Fe, releasing a tremendous amount of energy. This is the equivalent of detonating the entire world's nuclear arsenal on every cm^2 of the neutron star's surface within a minute! Some of these binaries can be amazingly close to one another. Here's an artist's conception of one particularly extreme case, that of 4U 1820-30, which has a binary period of just over 11 min! Too bad the distances are in miles...

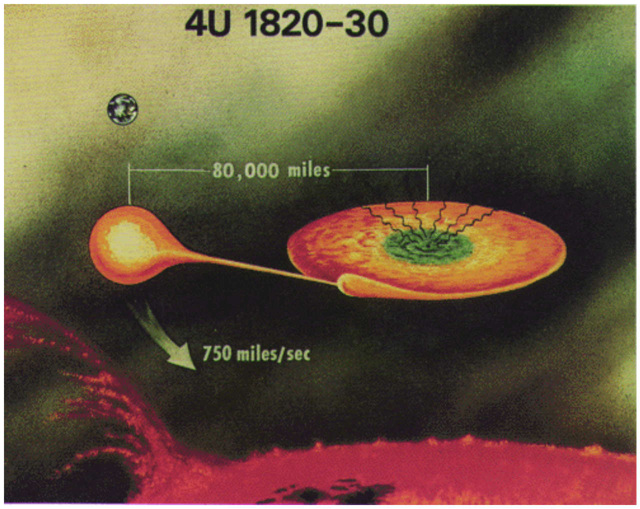


Illustration 85 : Neutron star in a binary system with accreting layer

If the companion to the Neutron star has a mass between 1 and 10 times our Sun's mass, the mass transfer is unstable and doesn't last very long, therefore, there are few objects in this category.

If the companion to the neutron star has a mass more than about 10 times our Sun's mass, the companion naturally produces a stellar wind, and some of that wind falls on the neutron star. The neutron stars in these systems have strong magnetic fields, around 10^{12} G (similar to typical isolated pulsars). At field strengths this high, almost all the accreting gas is forced to flow along field lines to the magnetic poles. This means that the X-rays primarily come from the resulting hot spots on the poles. It also means that, if the magnetic axis and rotation axis of the star are not co-aligned, the radiation sweeps past us once per rotation, and we see X-ray pulsations. These systems are therefore called *accretion-powered pulsars*, to distinguish them from the *rotation-powered pulsars* that Jocelyn Bell discovered.

For some recent results on accreting neutron Stars, check out a poster from a science fair for grownups held at the University of Chicago.

4.1.9 What The @#$% Makes γ-Ray Bursts?

γ-ray bursts have been known for more than 25 years, but there are still a lot of uncertainties about their origins. They were first discovered in the late 1960^s as part of nuclear test ban verification; US satellites picked up bursts of γ-rays, and there was a lot of concern that these might be due to Soviet nuclear explosions, but it was determined that the bursts originated outside the atmosphere. The *official* discovery came in 1973 (by Klebsedal, Olsen, and Strong). Since then more than 2,500 bursts have been detected, over 1,800 by BATSE (the Burst and Transient Source Experiment aboard the Compton γ-ray observatory). Before tackling the question of what γ-ray bursts are, we need to establish what they are observationally.

Loosely speaking, γ-ray bursts are, well, bursts of energy that appear mostly in γ-rays, and come from outside the Earth. The flux at Earth is between 10^{-8} and 10^{-3} erg/cm^2/s, the duration of the bursts is between 10 ms and 1,000 s, and the photons typically have energies between 100 keV and 2 MeV, although energies down to 5 keV and up to 18 GeV have been seen from some bursts. The flux as a function of time varies from burst to burst, but often a spike within a burst follows the *fred* profile (fast rise, exponential decay). Here's an animated gif showing a simulation of a burst as we'd see it on a map of the galaxy (left), and its brightness as a function of time (right). All in all, γ-ray bursts are extremely heterogeneous, Therefore, it is tough to extract characteristic behaviors that would lead to easy classification (see a typical time profile for a GRB).

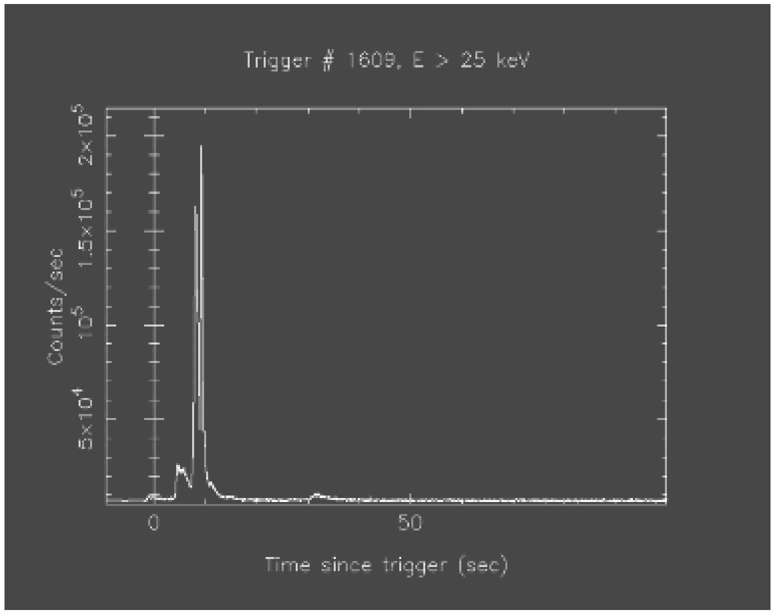


Illustration 86 : Typical time profile of a γ-ray burst

Can we at least tell how far away γ-ray bursts are?

Until recently, the answer was 'no', not with any certainty. From the early 1970s, it has been apparent that γ-ray bursts come from all parts of the sky with approximately equal probability. Since other aspects of γ-ray bursts (such as the fast rise time [<1 ms in some cases] and high photon energies) seemed consistent with a neutron star origin. Most people prior to 1990 believed that γ-ray bursts came from galactic neutron stars, and that instruments simply hadn't had the sensitivity to probe deeply enough to see a bias towards the galactic center and plane. However, since 1990 the 'Burst and Transient Source Experiment' (BATSE) aboard the Compton γ-ray observatory has seen nearly one γ-ray burst per day, and these too are nearly isotropic.

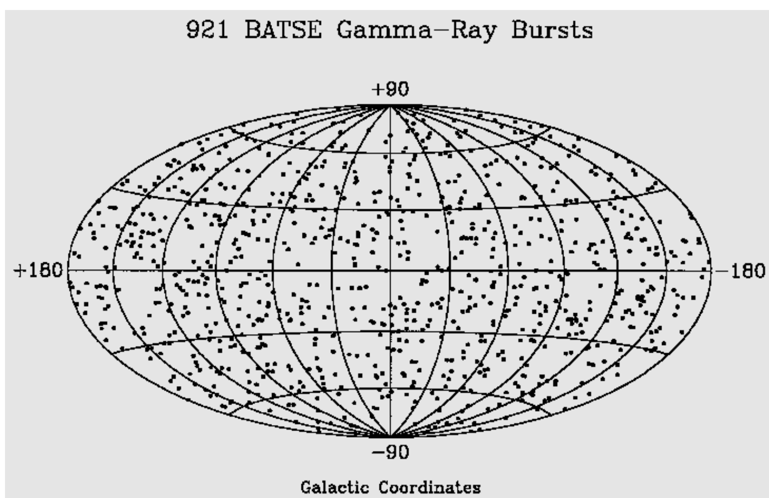


Illustration 87 : First 921 γ-ray bursts from BATSE

It is believed that, if galactic neutron stars really are the sources of γ-ray bursts, BATSE should be able to see them far enough away that the distribution should be more like a pancake than a sphere. Another piece of evidence comes from the number of sources seen with at least a given flux. If the universe were Euclidean, and the sources were spread out uniformly, then out to a distance *r* there would be a number of sources proportional to r^3, and the dimmest sources would have fluxes proportional to $1/r^2$. Thus, in a Euclidean universe with uniformly distributed sources of a given intrinsic luminosity, a plot of log *N* (*N* = number of sources at a flux > *F*) versus log *F* should have a slope of $-{}^3/_2$. At the highest fluxes, this slope is seen, but at lower fluxes, the slope becomes smaller, exhibiting a continuous rollover, and becoming about -0.8 at the lowest fluxes BATSE can see.

What does that mean?

The drop-off at lower fluxes, which corresponds to greater distances if the intrinsic luminosity is constant, means that in some sense there is an edge to the distribution. For example, if the sources were distributed in a thin plane instead of a sphere, the slope would be -1, and for sources in a line, the slope is -0.5. Even if the source distribution is spherical, the slope will roll over if the sources become less dense at greater distances, or if the flux drops off faster than $1/r^2$. Because of the isotropy of the distribution, many people believed that γ-ray bursts are cosmological, at typical redshifts z = 1, where the redshift would decrease the flux in about the right way to account for the log N – log F rollover. However, until 1997 there was not any '*smoking gun*' to tell us for sure that the bursts were cosmological, and, actually, there were plausible models of γ-ray bursts in which the bursts came from an extended halo around our own galaxy.

All this changed in 1997, when researchers using the Italian-Dutch satellite BeppoSAX made a tremendous breakthrough. A sticking point in our understanding of γ-ray bursts was that they were always a *one and done* type of phenomenon, in which, after a brief flash of γ-rays lasting a few seconds, that was all she wrote. The lack of any detectable emission in other frequencies (such as optical and radio) meant that these sources couldn't be localized with any certainty. This is where BeppoSAX came in. This satellite has the capability of detecting X-ray emission from half a dozen to a dozen γ-ray bursts per year, and localizing the emission to within about 2 arcmin (a 30^{th} of a degree, or a little less than the apparent size of a billiard ball at the far end of a football field). This is about 100 times better than the localization possible with BATSE. It allowed people to discover that most of the γ-ray bursts observed with BeppoSAX have X-ray afterglows.

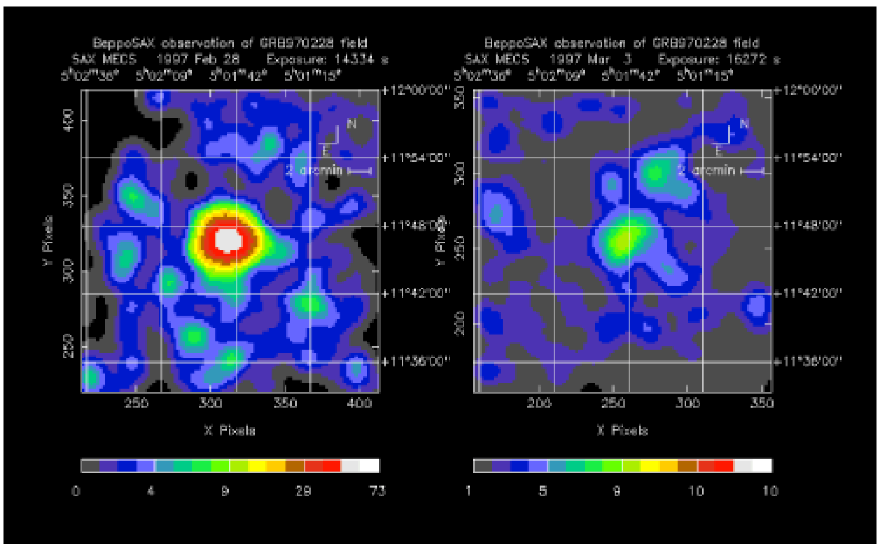


Illustration 88 : γ-ray burst with X-ray afterglow

Many have optical and radio afterglows as well! The afterglows in optical and radio allowed the position to be nailed down to an arcsec or better (the apparent size of an eyelash at the far end of a football field!). Further observations showed that, at least in projection and probably in reality, the γ-ray bursts are in galaxies. Not only that, but redshifts have been measured for many of these galaxies, and some of them are really big: one was measured at a redshift greater than 3.4! Therefore, that settles at least part of the question: the bursts observed with BeppoSAX are definitely cosmological. If γ-ray bursts are cosmological, their energy release must be gigantic. It is now thought that most bursts are tightly beamed (like a lighthouse), and emit a good 10^{51} ergs in just γ-rays. It is still really puzzling how this could happen. The constraints on these models are really tight, and no detailed model yet suggested can circumvent all the constraints. No matter what these are though, the energy release by itself guarantees that the central engine is one of the biggest blasts around! The two most popular current ideas are:

1. The bursts are caused by the inspiral and merger of two neutron stars or a neutron star and a black hole, or
2. The bursts are caused by the collapse of a massive star (maybe 20 solar masses or more) into a rapidly spinning massive black hole.

General opinion is that the longer bursts are of type (2), but there is still a question about the shorter bursts. Either way, it seems unavoidable that all that energy sails out into interstellar space, and produces a serious blast wave.

4.1.10 Soft γ-Ray Repeaters And Whopping Magnetic Fields

Another (somewhat less) mysterious type of bursting events believed to come from neutron stars is the soft γ-ray repeater bursts. These typically last from 0.1 s to 3 s, and have spectral peaks in the 10 keV to 30 keV range. Soft γ-ray repeaters have been identified in the past with supernova remnants, but with the possible exception of the single source in the 'Large Magellanic Cloud' (SGR 0525-66), these identifications are now considered dubious (see Gaensler et al. 2001, ApJ, 559, 963). Caution is especially appropriate, because there are only four (!) SGRs known (SGR 0525-66, SGR 1900-14, SGR 1806-20, and SGR 1627-41, where the numbers give the right ascension and declination in B1950 coordinates). Despite the paucity of these sources, interest has focused on them because:

1. They have observational properties distinct from that of any other known astronomical phenomenon.
2. They have some tantalizing links to γ-ray bursts.
3. One current model of SGRs involves neutron stars with 10^{14} - 10^{15} G surface magnetic fields, in which a variety of exotic microphysical processes could be important.

One particular burst from SGR 0525-66, which occurred on March 5, 1979, has attracted so much attention that it is usually called just the 'March 5 event'. This was the highest intensity γ-ray event seen up to that point. It started with a hard spike that lasted a ¼ of a second, and had a rise time less than a ms, then continued emitting softer radiation for another 200 s. The emission during this extended tail had a clear period of 8 s, and was consistent with rotational modulation. Because of the high intensity and rapid onset of this event, nine different satellites throughout the Solar System recorded this event, and the relative timing between the satellites allowed the direction of the event to be determined very accurately. It was determined that the event came from a direction consistent with the N49 supernova remnant in the Large Magellanic Cloud, putting it at a distance of somewhat more than 50 kp. At this distance, the initial hard spike had a peak luminosity of more than 10^{45} $^{ergs}/_{s}$. That is to say, in the first ¼ s of the burst this source put out as much energy as the Sun radiates in 3000 y! This is also the event that makes some astronomers think that SGRs are related to classical γ-ray bursts. If the hard spike is analyzed by itself, then its duration, light curve, and energy spectrum are indistinguishable from classical GRBs. Indeed, if the event had occurred 10 times as far away as it did (so that we would have missed the extended soft emission), we would have considered this another ho-hum γ-ray burst.

Observations of other bursts from SGR 0525-66 (none as spectacular as the March 5 event), and bursts from SGR 1900-14 and SGR 1806-20 suggested initially that all are associated with supernova remnants, but as mentioned above this has been challenged. Even if they are associated with the remnants, the sources are not at the center of the remnants; instead, they are off to the side by distances that would imply a velocity of 500-1500 $^{km}/_{s}$. The typical peak luminosity of a SGR burst is 10^{40} - 10^{42} $^{ergs}/_{s}$. This information can be put together as follows:

- The March 5 event displayed an 8 s rotational period. Black holes do not have solid surfaces to give such a coherent rotational period; therefore, it must be a neutron star.
- SGRs may (or may not!) be associated with supernova remnants. If they are not, most bets are off. On the other hand, if they are:
- supernova remnants leave behind neutron stars or black holes, so SGRs must be related to neutron stars or black holes.
- If the supernova remnant were more than about 100,000 years old, it would have dissipated; therefore, we could not see it. We can, thus the compact object producing the SGR must be relatively young.

If SGRs are associated with supernova remnants then they come from young neutron stars.

The next question is what is the energy source for the bursts?

One naturally thinks of accretion or rotation, but strong magnetic fields have also been considered.

If SGRs are associated with supernova remnants, they are moving at high speeds, because they are not at the center of the remnants. Accretion then has serious problems, because the high velocities inferred for all three SGRs mean that the neutron star can't pick up enough mass from the interstellar medium. In addition, it turns out that accretion from, e.g., asteroids would be expected to last tens of thousands of seconds instead of the observed tenths of seconds. Rotation has even greater problems. A neutron star spinning at an 8 s period, such as the one that produced the March 5 event, has only about 3 * 10^{44} ergs in rotational energy available. But the March 5 event itself released about 4 * 10^{44} ergs, and the X-ray energy released since then in persistent emission is another 3 * 10^{44} ergs, therefore, there isn't enough rotational energy to do the job.

Starting about 1992, Chris Thompson and Rob Duncan started proposing another energy source, that of very strong magnetic fields. They were drawn to this in part, because the March 5 event implies a very long rotational period (8 s) compared to the expected birth spin period of neutron stars (less than a second). If, as usually thought, the neutron star spins down by magnetic braking, then to get to that long period in the 5,000-year age of the N49 supernova remnant requires that the field be nearly 10^{15} G! Thompson and Duncan noticed that this would imply a total magnetic energy in the star of about 10^{47} ergs, which is easy enough. They also found that this model is consistent with the other properties of SGR bursts.

Therefore, maybe some neutron stars have magnetic fields of 10^{15} G.

So what? Given that we are sure that some neutron stars have fields of 10^{12} - 10^{13} G, which already sounds unbelievably large, what is the big deal with another two orders of magnitude?

The difference comes at the subatomic level. In a magnetic field a charged particle, such as an electron or proton, will spiral around the field at a preferred frequency, the cyclotron frequency that is proportional to the strength of the field. This principle is used in magnetic resonance imaging, where the preferred frequency (of nuclei) is in the radio wavelengths. When magnetic fields of neutron star's strength are introduced, the electron cyclotron frequency is in the X-rays, and when the field is $4.414*10^{13}$ G the electron cyclotron energy (the cyclotron frequency * Planck's constant) equals the electron rest mass energy.

This field turns out to be a critical field in quantum electrodynamics, such that (essentially) above that field there are a number of bizarre processes (e.g., single photon pair production, photon splitting) that can be very important, whereas below the critical field those processes are negligible. We do not have a prayer of accessing this regime of ultrastrong fields in the laboratory, and we only have our quantum mechanical predictions to guide us. Therefore, if we can establish that such fields exist in astronomy, then by studying those objects we can test our quantum mechanical theories in a new physical regime. First, we have to get more direct evidence that such high fields exist. Recent supporting evidence arrived in 1998, when several soft γ-ray repeaters were active, and when it was finally possible to measure:

1. A spin period
2. A rate of change of the spin period,

which in the simplest approximation allow an estimate of the magnetic field of these sources. You guessed it; it seems like magnetic fields greater than about 10^{14} G are required, although there are still some subtleties. What would really be nice would be a signature in the energy spectrum of these ultrastrong fields. We do not have it yet, but there has been a lot of effort by many people. Tomek Bulik and I have proposed the one that I think is most promising. It relates to something called the vacuum resonance, and the spectral signature is a dip in the X-ray spectrum that moves to lower energies when the intensity is higher. If such a signature is seen, we will then have strong and direct evidence for the existence of these superstrong fields, and theorists such as me will have a wonderful new playground!

4.2 The Doppler Effect

As we saw (of hummingbirds, trains, and the Doppler shift), the frequency of a wave increases when either an observer is moving toward a source or the source is moving towards the observer (or both). For the simplest derivation of the Doppler shift formula, we will examine the case where our observer is moving with velocity $\vec{\vartheta}_{observer}$ towards a stationary source that generates waves with wavelength λ_0. In this instance waves travel radially and concentrically outward from our source at a velocity $\vec{c}_{wave}$.

If we imagine that each of the blue concentric circles in the illustration below represents the peak of a wave, we see that the observer will encounter waves with a higher frequency (i.e. more waves per unit time). Since the observer is moving directly into the wave, thus encountering peaks more quickly than would happen if he or she were stationary. This situation is analogous to a jet-skier that is riding into the water waves, where the ride is arguably much rougher than when the jet-ski was standing still.

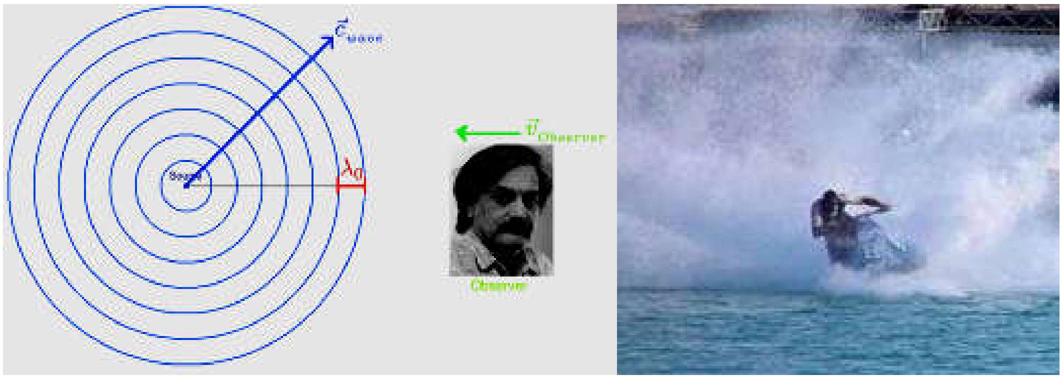


Illustration 89 : Acoustic Doppler Effect

When both the source and the observer are standing still in time *t*, a wave will traverse a distance of $\vec{c}_{wave} * t$. If the wavelength of the signal (sound, water, light, etc.) is λ_0, then the observer will see (or hear) *N* waves pass by, where:

$$N_{waves} = \frac{c_{wave} * t}{\lambda_0}$$

Equation 34 : Number of waves during time

(Note that we drop the vector notation of the wave (c_{wave}), since only the magnitude, or speed, is relevant here.)

If, however, the observer is moving toward the source at a speed of $\vartheta_{observer}$, he will travel an additional distance of $d = o_{observer} * t$. This means that we would now encounter an additional number of waves:

$$\Delta N_{waves} = \frac{_{observer} * t}{\lambda_0}$$

Equation 35 : Additional waves for a moving observer (towards wave source)

for a total of:

$$N'_{waves} = N_{waves} + \Delta N_{waves}$$

Equation 36 : Sum of waves for a moving observer

Thus, by dividing through by the time interval *t*, we recast our formula in terms of frequencies:

$$\frac{N'_{waves}}{t} = \frac{N_{waves}}{t} + \frac{\Delta N_{waves}}{t} \Rightarrow$$
$$f' = f_0 + \Delta f$$

Equation 37 : Observed frequency (approaching the source)

where *f′* is now our new observed frequency when we approach the source.

Now we can express *f′* using above equation as follows:

$$\begin{aligned} f' &= f_0 + \Delta f \\ &= \frac{c_{wave}}{\lambda_0} + \frac{\vartheta_{observer}}{\lambda_0} \\ &= \frac{c_{wave}}{\lambda_0} * \left(1 + \frac{\vartheta_{observer}}{c_{wave}}\right) \\ &= \underline{f_0 * \left(1 + \frac{\vartheta_{observer}}{c_{wave}}\right)} \end{aligned}$$

Equation 38 : Observed frequency (regardless moving direction)

It is important to note that $\vartheta_{\text{observer}}$ is negative if the observer is moving away from the source of waves.

Try your hand at combining the last two equations to show that the formula $\left(\frac{\Delta f}{f_0} = -\frac{\vartheta}{c}\right)$ follows immediately.

The equations for when the source is moving (or both source and observer are moving) turn out to be somewhat different, but it is interesting and important to note that when $\vartheta_{source} << c_{wave}$ and / or $\vartheta_{observer} << c_{wave}$, the results reduce to the same expression as given in the last equation.

5 Core-Collapse Supernova And Supernova Remnants

5.1 Core-Collapse Supernova

Last we learned about how neutron stars become the compact stellar objects that are left behind when massive stars (M_{star} > 10 M⊙) end their lives violently in a core-collapse supernova. Now we will explore the physical processes that explain these tremendous explosions.

As we discussed in the stellar evolution wiki article after the H is depleted in the core of a massive star, successive stages of fusion ensue in the core and around it. The figure below depicts the elemental makeup of these regions with the heavier elements appearing closer to the core. This is generally referred to as an onionskin make-up, but this is a grossly simplified view, as there would sometimes be mixing between layers as the star evolves. Moreover, there are other elements (such as S) in some of the layers, but the general idea applies. In particular, we must pay close attention to the Fe core enshrouded by a shell of Si and S burning material. This shell generates more Fe, which grows the cores mass. Unlike all other stages of the star's evolution, the final stage sees the fires of elemental fusion extinguish in the core.

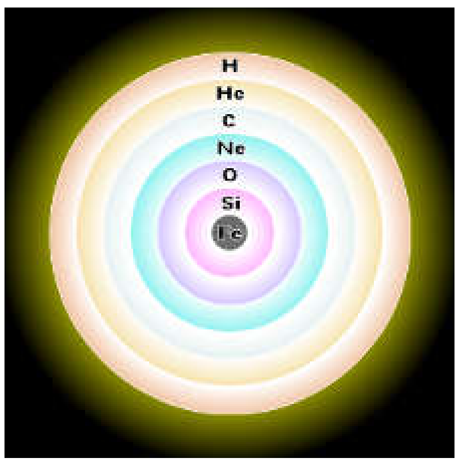


Illustration 90 : Shells of a star short before supernova explosion

This fate is ensured by the fact that, unlike all of the previous stages of nuclear fusion that *generated* energy, Fe *requires* energy to fuse into heavier elements. In a sense the core becomes a massive energy sink, and as its mass nears the Chandrasekhar limit (~ 1.4 M⊙), the atoms become relativistic (in addition to having the electrons degenerate), and the core begins to collapse, unable to exert the needed outward pressure to resist the pull of gravity towards the star's center.

The core of the star, about the size of earth, collapses until neutron degeneracy pressure can balance that of gravity. By this point, the core is about the size of Manhattan (~ 10 km). Let us take a short time-out on the action to explain the collapse in detail.

As the core collapses, all of the protons are transformed into neutrons through numerous physical processes. The simplest process is inverse-β decay, wherein a proton combines with an electron to become a neutron (neutral by the fact that electrons and protons have exactly the same magnitude charge, yet opposite in sign). In addition to forming a neutron, a neutrino is also emitted. Think of a neutrino as the near-massless, chargeless soul of the electron that has ceased to be; in this case it would be an electron neutrino, typically symbolizes as ϑ_{e^-}. After supernova 1987A exploded in the Large Magellanic cloud a massive stream of neutrinos was detected by way of anomalously high detection rate at neutrino detection experiments that were, and still are, housed far underground to shield against spurious detections not associated with cosmic events. We can visually represent this nuclear decay in a simple equation:

$$p^+ + e^- = n + \vartheta_{e^-}$$

Equation 39 : Nuclear decay

Note that for each neutron thus formed a neutrino is generated as well.

Now we pick up where the action left off.... The core reaches its minimum size of about 10 km, but then it begins to rebound. As it does, so shockwaves are driven into the stellar material that is also trying to fall in to the center. After this rebound, the core will again collapse, but this time it is more or locked into place as a fully formed neutron star. In certain respects, this resembles a ringing bell.

Meanwhile the shockwave drives through the infalling stellar material, and is strengthened by the tremendous flux of neutrinos that results from the neutron star formation. This shockwaves rips apart the star in an event we call a supernova. The diagram below shows a great cartoon and caption from the Wikipedia page on Type II Supernova and depicts the various stages of the core-collapse.

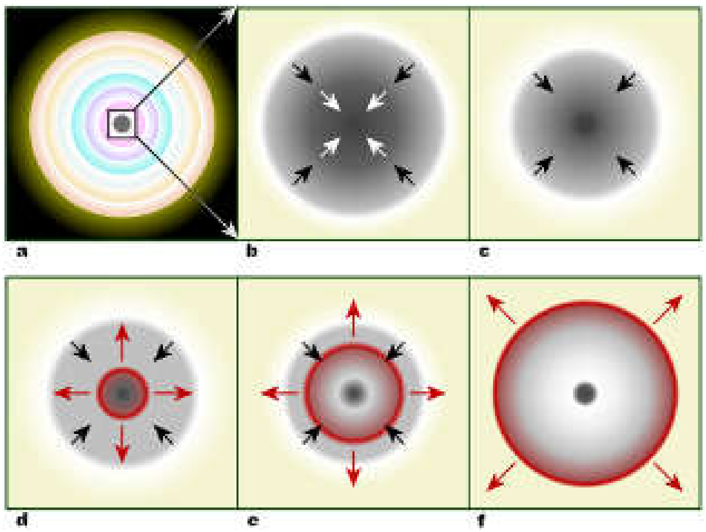


Illustration 91 : Core collapse (Type II supernova)

'Within a massive, evolved star (a) the onion-layered shells of elements undergo fusion, forming a Ni/Fe core (b) that reaches Chandrasekhar limit and starts to collapse. The inner part of the core is compressed into neutrons (c), causing infalling material to bounce (d) and form an outward-propagating shock front (red). The shock starts to stall (e), but it is re-invigorated by neutrino-interaction. The surrounding material is blasted away (f), leaving only a degenerated remnant.

Here is an animation I put together that shows this core collapse in motion!

Core Collapse

5.2 Supernova And Remnant Basics

5.2.1 What Are Supernova?

5.2.1.1 A Basic Definition

Supernovas are exploding stars. They represent the very final stages of evolution for some stars. Supernovas, as celestial events, are huge releases of tremendous energy, as the star ceases to exist, with about 10^{20} times as much energy produced in the supernova explosion as our Sun releases every second. Our Sun, fortunately, will not end its life as a supernova.

Currently, supernovas are only seen in galaxies other than the Milky Way. We know that supernova have occurred in our galaxy in the past, since both Tycho Brahe and his protégé Johannes Kepler discovered bright supernova occurring in the Milky Way in 1572 and 1604, respectively. The Chinese, and others, have records of a *guest star* occurring in 1054 in the present constellation Taurus. Today we see remnants of all three supernova, which appear as expanding clouds of gas where each was originally discovered. However, no supernova has been seen in our galaxy since Kepler's sighting.

Supernovas, when they are discovered, are designated by the year in which they are discovered, and the order in which they are discovered during that year by using members of the alphabet. For instance, the fourth supernova discovered this last year was named SN 1998D, which occurred in the galaxy NGC 5440.

The brightest supernova since Kepler's supernova was discovered on February 23, 1987, in the nearby galaxy, the Large Magellanic cloud (LMC). This supernova was easily seen with the naked eye throughout 1987 in the southern hemisphere. This supernova was named SN 1987A, and is still being observed by a number of telescopes, particularly the Hubble space telescope. Another bright recent supernova, observable from the northern hemisphere, was SN 1993J in the galaxy Messier 81 (M81).

As of 1998, January 1, 1270 supernova have been discovered since supernova first really began to be catalogued in 1885, when a supernova went off in the nearby Andromeda galaxy.

5.2.1.2 How Astronomers Study Supernova

When astronomers observe supernova, they do so today using telescopes working at various wavelengths. With optical telescopes, with which most of us are familiar, astronomers measure the amount of light being emitted by a supernova as seen from Earth, usually through a number of light filters. From these measurements they can determine how the luminosity, or brightness, and color of a supernova evolve, or vary with time. Supernova generally brighten to a maximum brightness, then decline slowly in brightness over many weeks or months.

Astronomers also pass the light through a device like a prism, which breaks the light from the supernova into its component colors. This is known as a spectrum. A spectrum shows how the brightness of light depends on the wavelength of light. Light is not equally bright at all wavelengths for supernova. In fact, the spectra of supernova vary over many weeks or months as well.

Both the *light curves*, as they are known, and the spectra of supernova tell astronomers about the physics that is occurring during and after the explosion. It is the nature of the explosion that is vitally important in understanding supernova, and learning which stars in galaxies blow up. Supernova are responsible for the production of many of the chemical elements in nature, and astronomers can study how these elements are produced, as well as estimating the amount of energy liberated in the explosion, and its effects on the star.

5.2.1.3 Types Of Supernova

The appearance of the spectrum allows astronomers to classify supernova into two main types: Type I and Type II. Basically, supernova arise from two very different classes of stars: massive ones and old non-massive ones. The Type II supernova very strongly show the presence of the element H in their spectra. Type I Supernova do not show any H in their spectra. The astronomer Rudolf Minkowski discovered this distinction in 1941, and this classification scheme was used for about five decades. It was thought that Type II supernova are the explosions of massive stars, whereas Type I supernova arise from old low-mass stars.

In about 1985, things got a little more complicated. Some Type I supernova discovered and studied in the early 1980^{s} appeared to be peculiar in nature. They did not exhibit a characteristic spectral signature, thought to be due to the presence of Si, seen in many other Type I supernova spectra. Additionally, a few of these peculiar supernova showed very strongly the presence of He. Furthermore, these supernova appeared to be occurring among populations of massive stars in galaxies. For these reasons it was realized that Type I supernova can be further subclassified into those with the Si spectral feature, these were called Type Ia supernova, and those that do not show this feature; this latter group were called Type Ib supernova.

Making affairs even more complicated (whew!), not all of the Type Ib supernova since 1985 have showed the presence of He in their spectra. These first cousins of Type Ib supernova are today called Type Ic supernova. More and more, supernova researchers have realized that the Type Ib/Type Ic distinction involves splitting hairs, and so many such supernova pundits put both of these Type I-subtypes into one main category: Type Ibc.

5.2.1.4 Where Supernova Occur

Supernova are seen to occur in galaxies all over the Universe. Galaxies are classified, basically, into three major groups: spirals, ellipticals, and irregulars. Now, Type II and Type Ibc supernova are seen to occur only in spiral and irregular galaxies, and these supernova also tend to be discovered in regions of these galaxies where star formation, particularly the formation of massive stars, most certainly has recently occurred in the last 10 million years or so. These supernova have not been seen in elliptical galaxies. It is therefore thought that these supernova arise from the explosions of massive stars in galaxies.

Type Ia supernova are discovered in all three types of galaxies, but Type Ia supernova are generally not found near massive star formation. Since very little, if any, star formation occurs today in elliptical galaxies, it is thought that Type Ia supernova arise from older, less-massive stars.

5.2.1.5 Theories about Supernova

In conjunction with this *environmental* evidence for the nature of supernova, astronomers who develop physical theories to explain celestial phenomena, and are therefore generally called theorists by their colleagues (as opposed to the other group of astronomers who are usually, more purely, observers), develop theoretical models to explain supernova explosions. Today these models involve sophisticated and complex computer simulations of the explosions. What the theorists tend to find is that stars more-massive than about 8 M⊙ become Type II and Type Ibc supernova. These are young, relatively massive stars, which form in spiral and irregular galaxies. They also find that the Type Ia supernova can best be explained by the explosion of somewhat exotic low-mass stars known as white dwarfs.

Stellar evolution is the study of how stars evolve and change, both internally and externally, throughout their lives. Stars generate their own energy during their lives by the process of nuclear fusion. The nuclei of lighter elements, such as H and He, are forced to fuse, or combine, under the tremendous pressures and temperatures at or near the centers of stars into the nuclei of heavier elements (The nucleus of an atom is the central body which generally contains protons and neutrons; for atoms and ions, electrons orbit the central nucleus. At the temperatures and pressures within stars, electrons are totally ripped free from the nuclei.).

As Albert Einstein discovered, in his famous mass-energy equivalence principle that everyone knows (but not nearly as many understand), $E = mc^2$, energy can be produced in large quantities from matter. When nuclear reactions occur inside stars, these reactions liberate huge amounts of energy, which inevitably trickles out from the star's interior to its surface, resulting in the light we see from the stars, their star shine.

In massive stars, those more massive than about 8 M⊙, the sequence of nuclear fusion progresses from the very simplest reaction of H-nuclei to form He-nuclei to more complicated reactions, involving the synthesis, as it is known, of Si-nuclei into Fe-nuclei. The Fe-nucleus is the most stable nucleus in Nature, and it resists fusing into any heavier nuclei, unless it is forced to do so with the input of truly formidable amounts of energy. As a result, when the central core, as it is known, of a star becomes pure Fe-nuclei, the core, which is generally the site of most of a star's energy production, is no longer able to produce energy, and therefore support the star. The core can no longer support the crushing force of gravity, resulting from all of the matter above the core, and the core therefore collapses under its own weight.

Some really exotic physics takes place during this core collapse. However, basically, only neutrons can generally survive the collapse, and when the neutrons act together under truly unimaginable crushing pressure to resist the collapse, the core becomes what is known as a neutron star. The core then becomes stable, but the rest of the massive star is left in limbo. The core collapse suddenly stops, and the core, like a squeezed sponge, bounces back, releasing a huge amount of energy, which rips through the outer layers of the star. The original massive star dies in a fiery explosion, with only the newly formed neutron star surviving this huge explosion.

The star has ended its life as a Type II or Type Ibc supernova. The death throes of this star occur extremely rapidly, over only a time of several ms! This compared to a star that, up to that point, had existed for several million years!

If the star began its life with a really large amount of mass, the theorists say that not even the neutrons at the star's core can hold back the crushing force of gravity. At that point, as the star ends its life, the core becomes a black hole. Possibly the result of the formation of the black hole is a supernova explosion, but some questions remain if this is really the chain of events for such very massive stars.

Now, this sort of evolution will not occur for the Sun. The Sun will continue to fuse very quietly its central H into He for the next five billion years or so. The core will become pure He, which will then fuse to C in a relatively short time. Finally, the C at the core cannot get hot enough to fuse into other type of nucleus. The C-core can no longer sustain the Sun's energy and collapses under its own weight, much as the more complex cores of massive stars do. However, electrons in the core act to resist the collapse, and the core of the Sun will become what is known as a white dwarf. As the formation of the central white dwarf occurs, the outer layers of the Sun will be sloughed off into space to form a planetary nebula. As the nebula disperses over many thousands of years, the skeletal white dwarf remnant of the previous Sun will sit in the galaxy, and glow away its residual heat over many billions of years.

White dwarfs, as you may suspect, are not very massive, since one will form from the core of the Sun, which today contains, by definition, 1 $M_\odot$. In 1938, the Indian astronomer Chandrasekhar determined that white dwarfs could not be more massive in the Universe than 1.4 $M_\odot$. If a white dwarf were to exceed this limit, called the Chandrasekhar limit, the star would cease to exist. Therefore, if a white dwarf finds itself in a binary system, where the two stars are close enough that their mutual gravity results in their interaction, then the binary companion may dump matter onto the white dwarf. The white dwarfs mass slowly and steadily increases to the point that it may exceed the Chandrasekhar limit. If this happens, then... poof! The white dwarf explodes in a Type Ia supernova and is completely destroyed. The matter that once was the white dwarf is incinerated into radioactive elements, which decay over time, and continue to power the light curve of the supernova.

5.2.1.6 The Effects Of Supernova

When Supernova explodes, they have profound effects on their surroundings in galaxies. The tremendous energy that is liberated affects the gas in its environment, pushing on it, and compressing it. If the gas was originally fairly dense, then the compressed denser gas can actually go on to collapse and form new stars. The energy of the explosion also synthesizes new elements, particularly those heavier than Fe. These fresh, new elements are then sprinkled into the surrounding gaseous medium, enriching it. Therefore, later generations of stars formed after the supernova contains more heavy elements than previous generations. In fact, the enrichment of the gas in our region of the Milky Way reached such a point that a sufficient quantity of heavy elements existed to give rise to life, as we know it, here on Earth. Supernova are thought to be directly responsible for us all!

Supernova also likely through small atomic and subatomic particles out into the galaxies, which we call cosmic rays. These particles, moving through the Milky Way, pass through space, and impinge on the Earth; it is thought that these high-speed, high-energy cosmic rays might be partially responsible for genetic mutation and, therefore, evolution of life here on Earth.

5.2.1.7 Supernova Tells Us About The Fate Of The Universe

Supernovas, particularly Type Ia supernovas, are intrinsically very bright, among the brightest objects in the Universe. As such, they can serve as beacons of light that can act as signposts indicating distances within space. Currently, astronomers are actively exploiting this fact about Type Ia supernova to measure the distances to very remote galaxies. It is thought that by determining these distances fairly accurately, and combining that information with the speeds at which the host galaxies are receding from us due to the expansion of the Universe originally studied most intently by Edwin Hubble, we can determine how much matter there is in the Universe, and, therefore, the Universe's ultimate fate. That is because, according to Einstein's theory of general relativity, the total amount of matter in the Universe determines what geometrical shape the Universe has. According to Einstein, matter curves the space and time around it. All of the matter in the Universe, of course, curves the entire Universe. The more matter, the more the curvature. The more curved the Universe, the more likely it is that the current expansion, resulting from the original Big Bang, will halt due to the force of gravity, and the Universe will collapse back on itself in a Big Crunch. Alternatively, if there's not enough matter to cause a Big Crunch, then the Universe will expand forever, with essentially no end.

Astronomers are locating these supernova by observing distant galaxies over and over. Quite often, they find bright, new objects appearing on their images. By taking the spectra of and producing light curves for enough distant supernova the astronomers can place constraints on the value of the mass of the Universe, and, therefore, determine whether it will collapse on itself or expand forever. Currently, new results seem to indicate that the amount of matter in the Universe is not enough to halt the expansion, but more results need to be obtained to verify these findings. The ultimate fate of the Universe is a profound question that humans have tried to answer. For creatures so used to beginnings and endings, having something last forever boggles the imagination. However, then, we are talking about the Universe.

5.2.2 Supernova Remnants

Ranking among the most energetic of astrophysical events, supernova result from either the core-collapse of a massive star, or from a white dwarf whose mass is pushed toward the Chandrasekhar limit, and ignites a thermonuclear explosion. In either case the light from the original explosion (powered by radioactive decays that release photons) fades with time, and the dominant source of light results from the interaction of the forward shock with the star's ambient surroundings, plus interactions with the reverse shock that heats the ejecta. The change in the dominant emission mode of radiation defines the transition between the supernova phase and the supernova remnant phase. This is a bit artificial since the physics that explains supernova remnants and their shocks is happening while still in the supernova phase, but is mostly hidden just like a candle held in front of a flood light is dimmed, even though it is there.

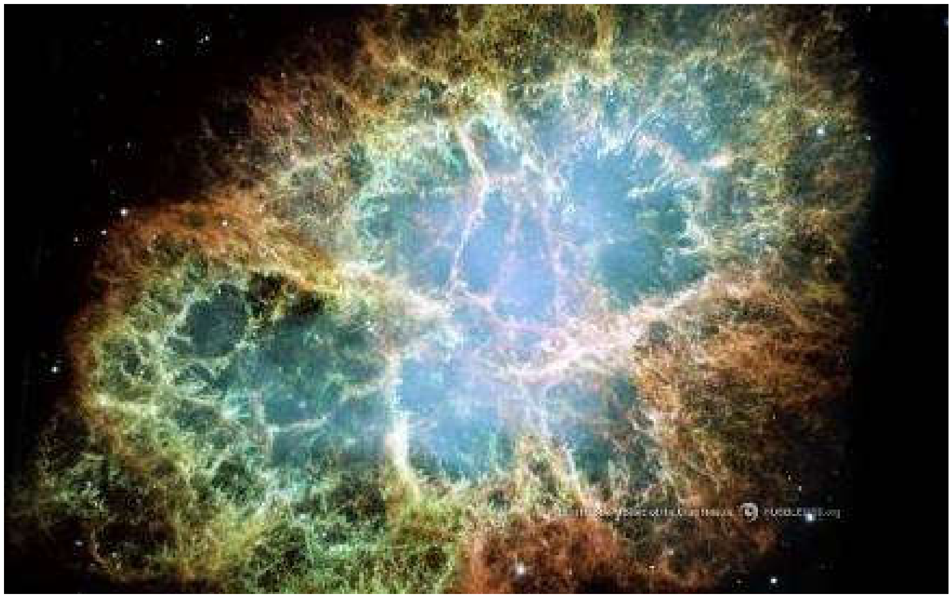


Illustration 92 : Crab Nebula, a supernova remnant

Supernova remnant (SNR) is a diffuse, expanding nebula that results from a supernova explosion. They are categorized into three main types based on their appearance, with the differences arising due to variations in initial progenitor and explosion conditions, density variations in the interstellar medium (ISM) and Rayleigh-Taylor instabilities.

The SNR consists of material ejected in the supernova explosion itself, as well as other interstellar material that has been swept up by the passage of the shockwave from the exploded star. Although not necessarily visible at optical wavelengths, SNRs tend to be powerful X-ray and radio emitters due to interactions with the surrounding ISM. They typically last several hundred thousand years before dispersing into the ISM, during which time they evolve through three main stages:

5.2.2.1 Free Expansion

When the supernova first explodes, a shockwave is sent out through the star. Once it has passed through the stellar material it continues to expand into the surrounding ISM creating a shockwave in the interstellar gas in the forward direction, and also a shock in the reverse direction, back into the supernova ejecta. This shocked material is heated to millions of K resulting in the emission of thermal X-rays.

The shockwave also accelerates the ISM into an expanding shell, which outputs copious amounts of synchrotron radiation due to the acceleration of electrons in the presence of a magnetic field. This expanding shell surrounds an area of relatively low density, into which the supernova ejecta expands freely, typically with velocities of around 10,000 $^{km}/_{s}$. This *free expansion* phase lasts for around 100 – 200 years until the mass of the material swept up by the shockwave exceeds the mass of the ejected material.

5.2.2.2 Adiabatic (Sedov-Taylor) Phase

As the mass of the ISM swept up by the shockwave increases, it eventually reaches densities, which start to impede the free expansion. Rayleigh-Taylor instabilities arise once the mass of the swept up ISM approaches that of the ejected material. These instabilities mix the shocked ISM with the supernova ejecta, and enhance the magnetic field inside the SNR shell. This phase lasts 10,000 - 20,000 years.

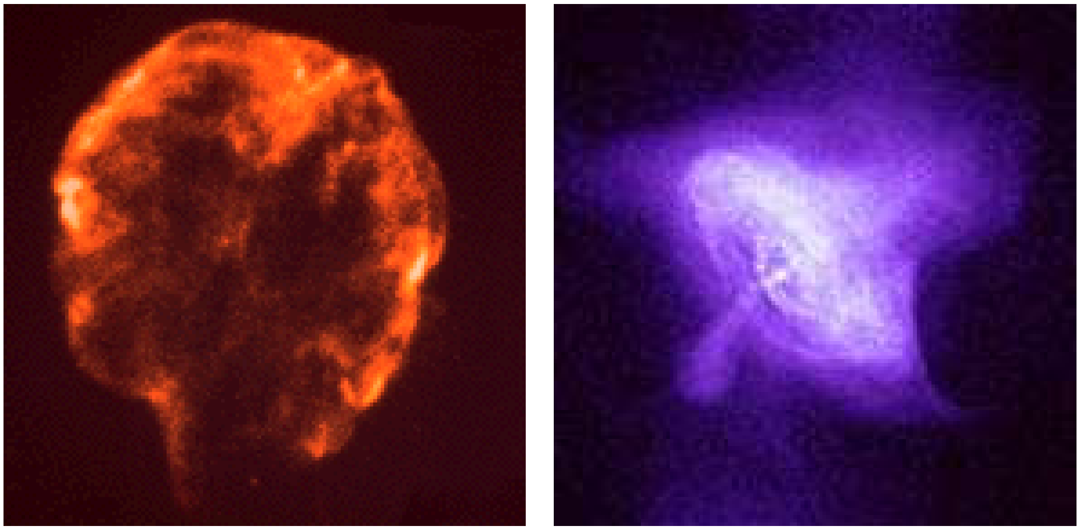
5.2.2.3 Radiative Phase

The shockwave continues to cool, and once temperatures drop below about 20,000 K, electrons start recombining to form heavier elements. This recombination process radiates energy much more efficiently than the thermal X-rays and synchrotron emission produced thus far, further cooling the shockwave, which ultimately disperses into the surrounding ISM.

Supernova remnants play a vital role in the evolution of galaxies. Apart from their role of dispersing the heavy elements made in the supernova explosion into the ISM, they provide much of the energy that heats up the ISM, and are believed to be responsible for the acceleration of galactic cosmic rays.

5.2.3 How Do We Classify Supernova Remnants?

A supernova remnant (SNR) is the remains of a supernova explosion. SNRs are extremely important for understanding our galaxy. They heat up the interstellar medium, distribute heavy elements throughout the galaxy, and accelerate cosmic rays.



Cygnus Loop in X-rays **Crab Nebula in X-rays**

Illustration 93 : Two samples of supernova remnants

5.2.3.1 Shell-Type Remnants

The *Cygnus Loop* (above left) is an example of a shell-type remnant. As the shockwave from the supernova explosion plows through space, it heats and stirs up any interstellar material it encounters, which produces a big shell of hot material in space. We see a ring-like structure in this type of SNR, because when we look at the shell there is more hot gas in our line of sight at the edges than when we look through the middle. Astronomers call this phenomenon limb brightening.

5.2.3.2 Crab-Like Remnants

These remnants are also called pulsar wind nebulae, or plerions, and they look more like a *blob* than a *ring* in contrast to the shell-like remnants. The nebulae are filled with high-energy electrons that are flung out from a pulsar in the middle. These electrons interact with the magnetic field in a process called synchrotron radiation, and emit X-rays, visible light, and radio waves. The most famous nebula is the *Crab Nebula* (above right), hence the common name, *Crab-like remnants*.

5.2.3.3 Composite Remnants

These remnants are a cross between the shell-type remnants and crab-like remnants. They appear shell-like, crab-like or both, depending on what part of the electromagnetic spectrum one is observing them in. There are two kinds of composite remnants: thermal and plerionic.

5.2.3.3.1 Thermal Composites

These SNRs appear shell-type in the radio waveband (synchrotron radiation). In X-rays, however, they appear crab-like, but unlike the true crab-like remnants, their X-ray spectra have spectral lines, indicative of hot gas.

5.2.3.3.2 Plerionic Composites

These SNRs appear crab-like in both radio and X-ray wavebands. However, they also have shells. Their X-ray spectra in the center do not show spectral lines, but the X-ray spectra near the shell do have spectral lines.

5.2.4 How Do We Know A Supernova Remnant's Age?

Naturally, if the supernova explosion was recorded in history, as is the case of many SNRs less than a few thousand years old, we know the age of the corresponding SNR. However, sometimes historians are not certain if a recorded *guest star* was a supernova or was the same supernova as a corresponding remnant. It is therefore important to be able to estimate the age of SNRs.

An easy way to guess the age of a SNR is to measure the temperature of the hot gas using X-ray spectroscopy. From this observation, we can estimate the velocity of the shockwave, and then infer the age from the shock velocity. This works because the velocity of the shock slows down with time as it engulfs more material and cools. This is easy to do but not very accurate, because there are a number of complicated processes that can heat up or cool down the gas, which are independent of shock velocity.

A better way, which works well for the youngest SNRs, is to measure a SNRs expansion over time, and apply the equation:

$$\text{rate} * \text{time} = \text{distance}$$

Equation 40 : Distance for youngest SNRs

For example, if we observed a supernova remnant both 20 y ago and today, we would have two images 20 y apart. Comparing the sizes of the two images, and dividing the difference by 20 y, yields the rate at which the SNR is expanding. For example, if we found that the supernova remnant expanded by 5 % over the 20 y-period, then the rate of expansion would be:

$$\begin{aligned}\text{rate} &= \frac{5}{20}[\text{years}] \\ &= 0.25\frac{1}{\text{year}}\end{aligned}$$

Because the SNR expanded 100 % since it exploded, its age can be calculated in the following manner:

$$\begin{aligned}\text{time} &= \frac{100}{0.25\left[\frac{1}{\text{year}}\right]} \\ &= 400\text{years}\end{aligned}$$

With the above example, it is safer to say that the supernova explosion happened less than 400 y ago, because it is quite likely that the SNRs expansion has slowed down since the explosion (whereas it is unlikely to have sped up). An age calculated according to this method is more likely to be accurate when calculated for the fasting moving features in the supernova remnant, or the result agrees with historical records.

5.2.5 Why Are Supernova Remnants Important To Us?

Supernova remnants greatly impact the ecology of the Milky Way. If it were not for SNRs, there would be no Earth, and hence, no plants or animals or people. This is because all the elements heavier than Fe were made in a supernova explosion, therefore, the only reason we find these elements on Earth or in our Solar System — or any other extrasolar planetary system — is because those elements were formed during a supernova.

The gas that fills the disk of the Milky Way is called the interstellar medium (ISM). In the parts of the galaxy where the ISM is most dense (for example, in the galaxy's spiral arms) the ISM gas can collapse into clumps. Clumps that are above a critical mass (somewhere between the mass of Jupiter and the Sun) will ignite nuclear fusion when the clumps gravitationally collapse forming stars. Therefore, the chemical composition of the ISM becomes the chemical composition of the next generation of stars.

Because supernova remnants introduce supernova ejecta (including the newly formed elements) into the ISM, if it were not for supernova remnants, our Solar System, with its rocky planets, could never have formed.

5.2.6 What Else Do SNRs Do To The galaxy?

In addition to enriching galaxies with heavy elements, supernova remnants release a great deal of energy to the ISM (10^{28} $^{Mt}/_{supernova}$). As the shockwave moves outward, it sweeps across a large volume of the ISM, impacting the ISM in two primary ways:

- The Shockwave heats the gas it encounters, not only raising the overall temperature of the ISM, but also making some parts of the galaxy hotter than others. These temperature differences help to keep the Milky Way a dynamic and interesting place.
- The shockwave accelerates electrons, protons, and ions (via the Fermi Acceleration process) to velocities very close to the speed of light. This phenomenon is very important, because the origin of the galactic cosmic rays is one of great outstanding problems in astrophysics. Most astronomers believe that most cosmic rays in our galaxy used to be part of the gas in the ISM, until they got caught in a supernova shockwave. By rattling back and forth across the shockwave, these particles gain energy and become cosmic rays. However, astronomers still debate to what maximum energy SNRs can accelerate cosmic rays — the current best guess is about 10^{14} $^{eV}/_{nucleon}$.

5.2.7 What Are The Life Stages Of An SNR?

The life stages of an SNR represent an area of current study. However, basic theories yield a three-phase analysis of SNR evolution:

In the first phase, *free expansion*, the front of the expansion is formed from the shockwave interacting with the ambient ISM. This phase is characterized by constant temperature within the SNR, and constant expansion velocity of the shell. It lasts a couple hundred years.

During the second phase, known as the *Sedov* or *adiabatic phase*, the SNR material slowly begins to decelerate by $\frac{1}{r^{\left(\frac{3}{2}\right)}}$, and cool by $\frac{1}{r^3}$ (*r* being the radius of the SNR). In this phase, the main shell of the SNR is Rayleigh-Taylor unstable, and the SNRs ejecta becomes mixed up with the gas that was just shocked by the initial shockwave. This mixing also enhances the magnetic field inside the SNR shell. This phase lasts 10,000 - 20,000 years.

The third phase, the *snow-plow* or *radiative phase*, begins after the shell has cooled down to about 10^6 K. At this stage, electrons begin recombining with the heavier atoms (like O); therefore, the shell can more efficiently radiate energy. This in turn cools the shell faster, making it shrink and become denser. The more the shell cools, the more atoms can recombine, creating a snowball effect. Because of this snowball effect, the SNR quickly develops a thin shell, and radiates most of its energy away as optical light. The velocity now decreases as $\frac{1}{r^3}$. Outward expansion stops, and the SNR start to collapse under its own gravity. This lasts a few hundreds of thousands of years. After millions of years, the SNR will be absorbed into the interstellar medium, due to Rayleigh-Taylor instabilities breaking material away from the SNRs outer shell.

5.3 Mach 1000 Shockwave lights Supernova Remnant

When a star explodes as a supernova, it shines brightly for a few weeks or months before fading away. Yet the material blasted outward from the explosion still glows hundreds or thousands of years later, forming a picturesque supernova remnant.

What powers such long-lived brilliance?

In the case of Tycho’s supernova remnant, astronomers have discovered that a reverse shock wave racing inward at Mach 1000 (1000 times the speed of sound) is heating the remnant, and causing it to emit X-ray light.

'We wouldn't be able to study ancient supernova remnants without a reverse shock to light them up,' says Hiroya Yamaguchi, who conducted this research at the Harvard-Smithsonian Center for Astrophysics (CfA).

Tycho's supernova was witnessed by astronomer Tycho Brahe in 1572. The appearance of this *new star* stunned those who thought the heavens were constant and unchanging. At its brightest, the supernova rivaled Venus before fading from sight a year later.

Modern astronomers know that the event Tycho and others observed was a Type Ia supernova, caused by the explosion of a white dwarf. The explosion spewed elements like Si and Fe into space at speeds of more than 11,000 $^{miles}/_{hour}$.

When those ejecta rammed into surrounding interstellar gas, it created a shockwave - the equivalent of a cosmic *sonic boom*. That shockwave continues to move outward today at about Mach 300. The interaction also created a violent *backwash* - a reverse shockwave that speeds inward at Mach 1000.

'It is like the wave of brake lights that marches up a line of traffic after a fender-bender on a busy highway,' explains CfA co-author Randall Smith.

The reverse shockwave heats gases inside the supernova remnant, and causes them to fluoresce. The process is similar to what lights household fluorescent bulbs, except that the supernova remnant glows in X-rays rather than visible light. The reverse shockwave is what allows us to see supernova remnants, and study them hundreds of years after the supernova occurred.

'Thanks to the reverse shock, Tycho's supernova keeps on giving,' says Smith.

The team studied the X-ray spectrum of Tycho's supernova remnant with the Suzaku spacecraft. They found that electrons crossing the reverse shockwave are rapidly heated by a still-uncertain process. Their observations represent the first clear evidence for such efficient, *collisionless* electron heating at the reverse shock of Tycho's supernova remnant.

The team plans to look for evidence of similar reverse shockwaves in other young supernova remnants. These results have been accepted for publication in '**The Astrophysical Journal**.'

Headquartered in Cambridge, Mass., the Harvard-Smithsonian Center for Astrophysics (CfA) is a joint collaboration between the Smithsonian Astrophysical Observatory and the Harvard College Observatory. CfA scientists, organized into six research divisions, study the origin, evolution, and ultimate fate of the Universe.

5.4 Schematics of Shock Structure

Below I have included a schematic of the two shock structures found in supernova remnants. This profile is a one-dimensional representation with the x-axis being the radius (from the explosion center), and the y-axis representing the density of material. It is a *snapshot* in time, and approximates the current state of the Cas-A system. Understanding the particle density in these shocks is critical, because the emission of radiation from these shockwaves depends on the density of particles at a given location. Higher density implies more radiation.

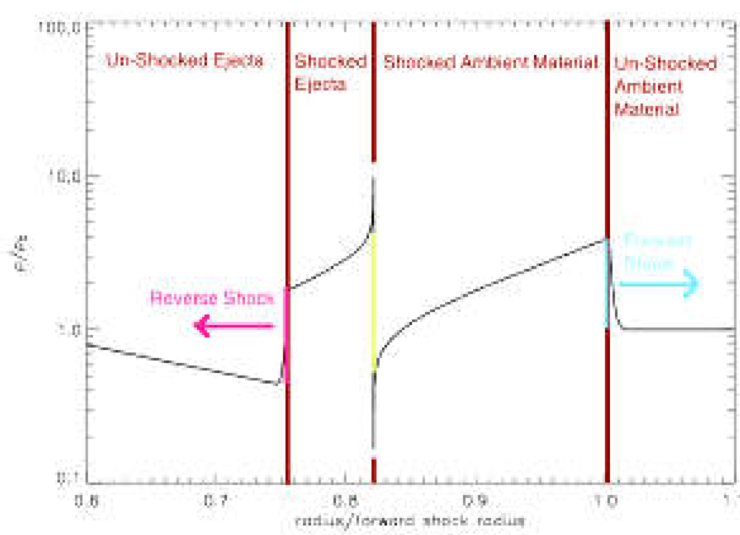


Illustration 94 : Shock structure found in supernova remnants

6 Galaxy Clusters / Dark Matter, Black Holes And Hubble's Law / Constant

6.1 Groups & Clusters Of Galaxies

galaxy clusters are the largest gravitationally bound objects in the Universe. They have three major components:

1. Hundreds of galaxies containing stars, gas and dust;
2. Vast clouds of hot (30 – 100 * 10^6 °C) gas that is invisible to optical telescopes;
3. Dark matter, a mysterious form of matter that has so far escaped direct detection with any type of telescope, but makes its presence felt through its gravitational pull on the galaxies and hot gas.

The hot gas envelopes the galaxies, and fills the space between galaxies. It contains more mass than all the galaxies in the cluster. Although the galaxies and hot gas clouds are very massive, scientists have determined that about 10 times more mass is needed to hold the cluster together. Something, namely dark matter, must exist to provide the additional gravity.

Astronomers think that galaxy clusters form as clumps of dark matter, and their associated galaxies are pulled together by gravity to form groups of dozens of galaxies, which in turn merge to form clusters of hundreds, even thousands of galaxies.

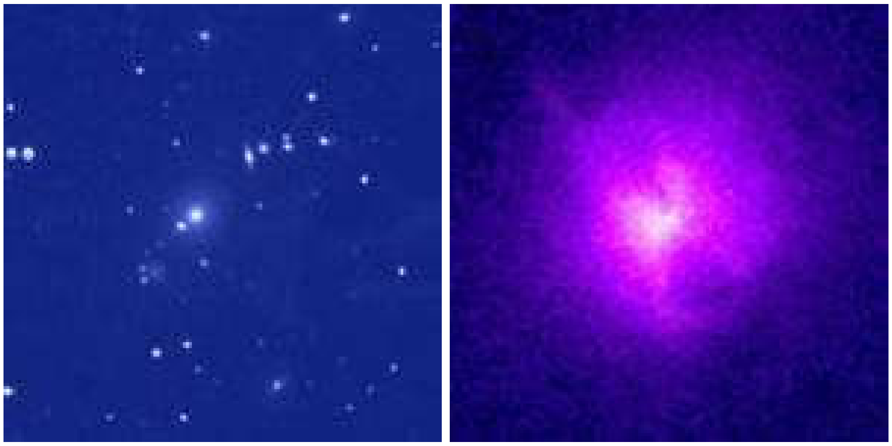


Illustration 95 : Comparison of optical images

From La Palma & B. McNamara (left) and X-ray image from CHANDRA (right) of the Hydra A cluster of galaxies. This cluster is so large that it takes light millions of years to cross it.

The gas in galaxy clusters is heated as the cluster is formed. This heating can be a violent process as gas clouds enveloping groups of galaxies collide and merge to become a cluster over billions of years.

CHANDRA images provide dramatic evidence of these mega-mergers. Cosmic *weather systems* millions of ly across are observed, as relatively cool 50,000,000 °C clouds of gas fall into much larger and hotter clouds.

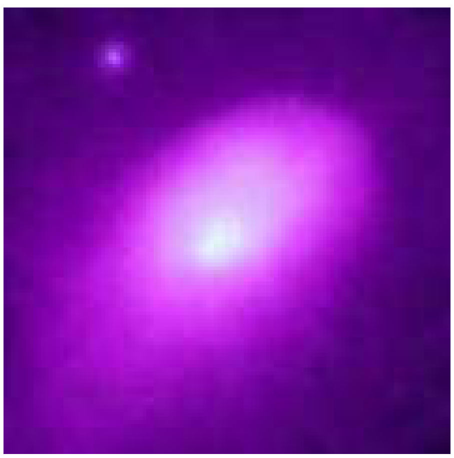


Illustration 96 : CHANDRA image of the galaxy cluster Abell 2142 in X-rays

It takes a long time to build a galaxy cluster. Exactly how long depends on details such as the amount of dark matter in the universe, whether the dark matter is hot or cold, how fast the universe is expanding, etc. The pressure in the hot gas is an accurate probe of the amount of dark matter in clusters of galaxies. By using this information and X-ray surveys to count, the number of large clusters in the Universe astronomers can test the various theories for the content and evolution of the Universe.

CHANDRA observations of the clouds of hot gas in clusters of galaxies will provide other clues to the origin, evolution, and destiny of the Universe. Combined X-ray and microwave observations can measure the effect of the cluster gas as it scatters the cosmic microwave background streaming through the cluster from the depths of the Universe. The amount of scattering makes it possible to estimate the distance to the cluster. This information can be used to estimate the size and age of the Universe.

Another intriguing question is the ultimate fate of the colossal gas reservoirs in galaxy clusters. The crush of all the gas and dark matter in the cluster pushes the particles in the center of the cluster closer together. This causes them to collide more frequently, and lose their energy to radiation to slowly, like a tire with a slow leak. In a billion years or so, this radiation leak will take its toll, and, if there is no energy source to offset the losses, the gas will cool and slowly settle – in what is called a cooling flow – onto a massive galaxy in the center of the cluster.

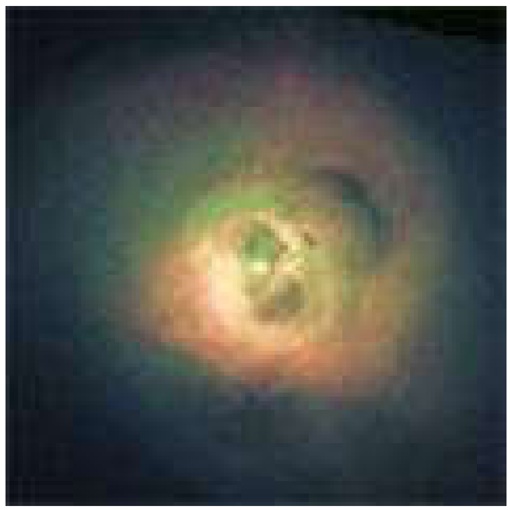


Illustration 97 : Core of the Perseus Galaxy cluster in X-rays

Early X-ray observations indicated that the cooling was occurring at such a rate that hundreds of new stars or cool gas clouds should be forming every year in the centers of many clusters. As astronomers began searching for this cool matter, they found some, but not nearly enough.

New observations of galaxy clusters by CHANDRA and the XMM Newton X-ray observatory, together with radio observations, may point to a resolution of this problem. They show that in a number of cases the inflow of cooling gas appears to be deflected by magnetic fields, and perhaps heated by explosions from the vicinity of a supermassive black hole at the core of the central galaxy. Whether or not such violent activity will explain the shortage of cool gas should become clear in the next few years.

Appendix

1 List of Equations

2 List of Illustrations

3 List of Tables

4 List of Videos